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"Panta Rhei—Everything Flows": Change in hydrology and society—The IAHS Scientific Decade 2013–2022

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Abstract The new Scientific Decade 2013–2022 of IAHS, entitled "Panta Rhei—Everything Flows", is dedicated to research activities on change in hydrology and society. The purpose of Panta Rhei is to reach an improved interpretation of the processes governing the water cycle by focusing on their changing dynamics in connection with rapidly changing human systems. The practical aim is to improve our capability to make predictions of water resources dynamics to support sustainable societal development in a changing environment. The concept implies a focus on hydrological systems as a changing interface between environment and society, whose dynamics are essential to determine water security, human safety and development, and to set priorities for environmental management. The Scientific Decade 2013–2022 will devise innovative theoretical blueprints for the representation of processes including change and will focus on advanced monitoring and data analysis techniques. Interdisciplinarity will be sought by increased efforts to connect with the socio-economic sciences and geosciences in general. This paper presents a summary of the Science Plan of Panta Rhei, its targets, research questions and expected outcomes.

Key words hydrology; environment; socio-hydrology; change; IAHS decade

"Panta Rhei—Tout s'écoule": Changement hydrologique et sociétal—La Décennie Scientifique 2013–2022 de l'AISH

Résumé La décennie scientifique 2013–2022 de l'AISH est intitulée "Panta Rhei—Tout s'écoule" et est dédiée à des activités de recherche concernant la question du changement hydrologique et sociétal. La vocation de "Panta Rhei" est d'atteindre une meilleure compréhension des processus régissant le cycle de l'eau en se concentrant sur leur dynamique de changement, en lien avec les systèmes anthropiques qui changent eux–mêmes rapidement. L'objectif opérationnel est d'améliorer notre capacité à prévoir la dynamique des ressources en eau au service d'un développement sociétal durable dans un environnement changeant. Le concept implique une focalisation sur les systèmes hydrologiques vus comme une interface changeante entre environnement et société, dont les dynamiques sont essentielles à la sécurité hydrique, au développement humain, et au choix de priorités dans la gestion de l'environnement. La décennie scientifique 2013–2022 vise la conception de schémas théoriques innovants pour représenter les processus et leur évolution, et insistera sur les techniques avancées d'observation et d'analyse de données. On recherchera l'interdisciplinarité avec les sciences socio-économiques et les géosciences en général. Cet article présente une synthèse du programme scientifique "Panta Rhei", ses objectifs, ses questions de recherche et les résultats que l'on en attend.

Mots clefs hydrologie; environnement; socio-hydrologie; changement; décennie de l'AISH

"Δὶς ές τὸν αύτὸν ποταμὸν ούκ ἂν έμβαὶης" ("*You cannot step twice into the same stream*")
(Heraclitus of Ephesus, quoted in Plato's *Cratylus* 402a)

"智者乐水，仁者乐山。智者动，仁者静；智者乐，仁者寿" ("The wise enjoy water, the compassionate enjoy mountains. The wise are active and happy; the compassionate are quiet and have long lives.")
Confucius

INTRODUCTION

One of the missions of the International Association of Hydrological Sciences (IAHS) is to advance the science of hydrology for the benefit of society, with particular emphasis on parts of the world that suffer from severe water problems. IAHS has a long and well-known track record in undertaking a range of activities that improve hydrological knowledge and practice globally (www.iahs.info, IAHS 2012). The enthusiastic interest that the world-wide hydrological community dedicated to the IAHS Scientific Decade 2003–2012 on Prediction in Ungauged Basins (PUB; Sivapalan *et al.* 2003), and the relevant research results that this community effort generated (Blöschl *et al.* 2013, Hrachowitz *et al.* 2013, Pomeroy *et al.* 2013) clearly prove that the IAHS research initiatives play a leading role in shaping the evolution of hydrological science. One of the reasons for such interest is the "grand scale" of the challenges that the IAHS decades are tackling, which demand improved science networks and collaboration over geo-political and disciplinary boundaries (Ostrom 2009). The PUB Decade demonstrated that the community was engaged by the idea of collaborative research efforts to identify and address an important emerging research issue. The results of PUB in terms of education of young scientists, comparison of research views and results, and international cooperation and visibility were substantial. The success of PUB motivated the IAHS to propose a new initiative for the Scientific Decade (SD) 2013–2022, to continue to collectively address the most exciting research challenges related to the water cycle, water risks and water resources.

To identify the subject of the SD, an extensive consultation with the hydrological scientific community was promoted through a dedicated web discussion (see the IAHS blog, linked at www.iahs.info, in this paper quotations from this blog are denoted by the name of the contributor followed by "IAHS Blog"), which was widely advertised, received thousands of visits and collected many posts and comments. Moreover, a series of dedicated symposia was organized where senior and young scientists shared their views on the future of hydrology. The attendance at these meetings was impressive, another indication of a growing interest in cooperative scientific efforts. The consultation was an unprecedented success in terms of involvement of people, discussions and exchange of ideas, which, supported by the use of modern communication technologies, promoted a new spirit of global inclusivity. Every statement of this world-wide discussion was taken into account in shaping the SD plan, exemplifying an effective bottom-up process. The consultation provided a lesson that is coherent with the remit and background of IAHS: *the development of hydrological sciences is strictly related to the capability of the scientific community to profit from cooperative efforts through an effective synthesis, by stimulating, coordinating and valorising individual ideas*.

The scientific discussion clearly demonstrated that policy makers, water resources managers, stakeholders and scientists are well aware that the relationship between water and humans is more delicate today than ever (Postel 1992, Oki *et al*. 2006, Vogel 2011, Sivapalan *et al.* 2012, Srinivasan *et al.* 2012), therefore raising relevant concerns about water management (and related ethical issues, see Falkenmark and Folke 2002) and water security. The latter is defined as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems. This definition clearly highlights the important role of water for society to ensure peace and political stability today.

Population growth and increasing urbanization make society more dependent on water. However, somewhat paradoxically, perception by people of the relevant problems connected with water generally decreases with increasing societal development (Di Baldassarre *et al.* 2013a). Indeed, these days there are many individuals who do not need to personally secure water and assess water-related risks, such that their social contact with natural water systems is lost, along with their individual capability to assess their state: in such a situation one may tend to assume that water is not a personal problem. Therefore, the hydrological community is increasingly required to advocate sustainable development, by further evolving water resources awareness and management into the future (Rahaman and Varis 2005).

We live in a highly dynamic world with many changes occurring simultaneously. From an environmental perspective, the attention of the media is frequently focused on climate change, while this is only one of the many changes that are occurring (Varis *et al.* 2004) and not necessarily the most important. Amongst such changes, global population growth is perhaps the most compelling reason for concern (Fischer and Heilig 1997, Koutsoyiannis *et al.* 2009a). There is a remarkable increase of population in less developed countries, while other countries (such as Russia and those of Eastern Europe) are experiencing population decrease (Koutsoyiannis 2011). There are also significant population movements (Falkenmark and Widstrand 1992), both towards cities and between countries (e.g. Latin America to North America, Africa and Eastern Europe to Western Europe, etc.). As a consequence, there is an increase in the proportion of people living in cities that has significant implications for urban water management (Roy *et al.* 2008), and potentially a decrease in the level of connectedness that citizens have with their environment. Population growth leads to greater demand for food, electricity and industrial processes and, hence, greater demand on water (Golubev and Biswas 1984). Greater affluence in significant segments of society leads to further demands on water (Postel *et al.* 1996). Moreover, the increasing attention on human health implies an increasing need for potable water and water for sanitation.

These shifts in population dynamics are also induced by changes in the political geography of the world. For instance, the breakdown of the Soviet Union and the expansion of the European Union triggered population movements from Eastern to Western European countries, and also gave rise to new institutions and new legislation that has direct or indirect influences on water management. Such developments have a relevant impact on transboundary water resources management (Kliot *et al.* 2001).

Some hydrological and societal changes are the result of natural forces and some are human-induced. Some are relatively slow and some are sudden. Some are predictable and others unexpected and take society by surprise. The connections among these changes are considerable, because the inherent links between society and environmental systems are co-evolving.

In principle, change is a well-known concept; hydrologists have always had the perception that water systems are changing, at the very least because the Earth is in a constant state of change. Climate and the water cycle are continuously undergoing significant shifts that, in some cases, are perceived even during one's lifetime (Huss *et al.* 2009, Petrone *et al.* 2010, Kundzewicz 2011, Wilby and Keenan 2012, Koutsoyiannis 2013). However, it is evident that societal actions are now conditioning hydrology in many countries at a tremendous and increasing rate (Biswas 1981, Ren *et al.* 2002, Nilsson *et al.* 2005, Liu *et al.* 2009, Di Baldassarre *et al.* 2010, Vörösmarty *et al.* 2010, Ren *et al.* 2012). On the one hand, this development is beneficial for the health and wealth of people, but, on the other hand, it induces a significant stress on water systems (WWAP 2012). It is clear that water is becoming a major limiting factor to the sustainable development of society (Shiklomanov and Rodda 2003, Cudennec *et al.* 2007, Kundzewicz *et al.* 2008, Koutsoyiannis *et al.* 2009a, Koutsoyiannis 2011, EEA 2012, OECD 2012). In such a critical situation, water security is likely to become an emerging issue for many countries in the world, as highlighted in the eighth phase of the International Hydrological Programme of UNESCO (UNESCO-IHP 2012) and at the United Nations 2013 World Water Day (UN-Water 2013).

Strategies for sustainability generally require significant employment of economic resources. Also, the current global economic crisis demonstrates that strategic and efficient efforts for water management, within an interdisciplinary approach, are needed to ensure sustainable water uses for the future (Sivakumar 2011, Srinivasan *et al.* 2012). Thus, connections must be strengthened between hydrology and the geosciences in general, and with society, to provide stakeholders with a clear perspective of the priorities and advanced solutions for ensuring sustainable development (Cortner and Moote 1994, Post and Moran 2011).

Changing conditions demand that societies adapt, which can be done in two ways: by mobilizing more water or by managing the water demand (Falkenmark and Lannerstad 2005). Both options require prognoses based on a deeper knowledge of hydrological changes and their long-term developments in order to design efficient and sustainable measures. Therefore, improving water resource management implies that a better understanding is gained of the reaction of the hydrological cycle to the significant changes that the Earth system is experiencing today, in terms of environmental conditions and human pressure (Falkenmark and Rockström 2004). In particular, from a technical point of view, the phenomena connected with the water cycle (for instance floods, droughts, freshwater availability, circulation, distribution and quality) need to be more reliably simulated and predicted in systems that are heavily influenced by change, whether human-induced or natural (Dessai and Hulme 2007, Wagener *et al.* 2010, Sivapalan 2011, Di Baldassarre *et al.* 2013b, Haasnoot *et al.* 2013, S. Schymanski IAHS Blog).

To date, hydrological analyses focusing on the interaction between connected systems have mainly been carried out by considering each system (and related models) separately. Hydrological models have been identified, conceived and parameterized independently of potentially important co-evolutionary processes. As a result, our models of hydrology are particularly suited to simulate and predict processes for catchments in pristine conditions, and the interaction with society has been simulated by coupling them with independently developed models of societal behaviour. Within this framework, feedbacks between models are schematized by introducing selected links between input and output variables as boundary conditions, and the structure of such systems has typically been assumed to be fixed in time. Such a framework may account for hydrological changes induced by shifts in external forcings or internal dynamics, but cannot account for more complex changes due to co-evolving model structures or parameters. Nonetheless, this has provided a practical solution to solve water resources management and engineering problems in the short and, in some cases, long term (Kiang *et al.* 2011, Post *et al.* 2012).

As an example, Integrated Water Resources Management (IWRM) at the basin scale (Teclaff 1967)—which originates from works such as those of Mass *et al.* (1962) and Kneese (1964) in the early 1960s—has been one way in which the water community has successfully addressed the complex interactions between water and humans (Savenije and van der Zaag 2008) and investigated equitable allocations (Wolf 2009). This approach has been widely adopted by political decision makers in many countries. Within this framework, the impact of change was mainly assessed by using scenario analysis (Mahmoud *et al.* 2009, Haasnoot and Middelkoop 2012), with limited attention given to feedbacks, co-evolution and non-stationarity in system behaviour.

With the current acceleration of human impacts, it is becoming increasingly clear that improved accounting for change, interactions and feedbacks is necessary to reach a better interpretation of coupled human–natural systems (Matalas *et al.* 1982, Jarsjö *et al.* 2012). In particular, hydrological science should not be separated from management (Nalbantis *et al.* 2011). The future of hydrology is closely related to improving our understanding of changing behaviours of hydrological systems through the study of their two-way interaction with connected processes (Baresel and Destouni 2005, 2007, Wagener *et al.* 2010, Schaefli *et al.* 2011). In particular, it is necessary to study and represent the connection between water and humans more deeply, as this is one of the main drivers of change and is connected to both sustainable water use and sustainable development (a concept embodied in socio-hydrology, see Sivapalan *et al.* 2012) (see also: Fig. 1, Liu *et al.* 2008, Savenije and van der Zaag 2008, Brookshire *et al.* 2012, Huang *et al.* 2013). In this context, hydrological and connected models should not be developed independently, but through an improved understanding of their complex connections. To achieve this, interdisciplinary cooperation is needed to develop approaches that represent co-evolving systems in water resources modelling meaningfully.

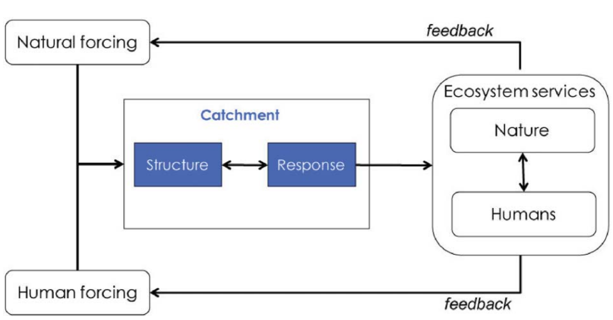

Fig. 1 Feedback between catchment, ecosystem services and human and natural forcings.

Therefore, the consultation process reached the conclusion that the IAHS Scientific Decade 2013–2022 should focus on “Change in Hydrology and Society”, where the conjunctive term “and” between hydrology and society indicates that particular focus is placed on the interaction and feedbacks between the two. It is relevant to note that the SD will develop at the same time as the “Future Earth” initiative, a major 10-year programme starting in 2013 that brings together natural and social sciences through cooperation between the International Council for Science (ICSU), the International Social Science Council (ISSC) and other major international organizations. Since water is a key element underpinning societal sustainability, seeking the connections and the synthesis of the research results of the two initiatives will represent a unique opportunity to foster interdisciplinarity.

The present paper presents the science and implementation plan for the SD 2013–2022. IAHS looks forward to a most rewarding decade of hydrological research that will invigorate the research community while addressing the needs of society.

PERSPECTIVES IN MONITORING, DATA ANALYSIS AND RESEARCH FACILITIES IN HYDROLOGY FOR THE NEXT 10 YEARS

Looking back 10 years in the world of hydrological sciences, one notes that research has changed dramatically. New methods and new research styles have been introduced, as well as new research philosophies that have changed the way hydrological problems are considered. The major changes were due to the increased availability of computing power and of different types of data (especially global-scale remotely sensed data), the increased visibility of research results due to the widespread diffusion of web-based publishing, and the increased number of avenues for publication and of research groups working in hydrology all over the world. However, notwithstanding the continued efforts of IAHS to support networking and knowledge consolidation (Rodda 1981, Hubert 2002, Koutsoyiannis and Kundzewicz 2007, Cudennec and Hubert 2008, IAHS 2012), fostering lasting connections among research groups remains a challenge, and continued effort towards community building, knowledge aggregation, synthesis and dissemination is essential.

Looking forward to the next 10 years, one realises that even more dramatic changes are likely to occur in research opportunities and practices. Computer capability will continue to increase, thus providing the potential to support new data analysis and verify new theories and approaches (Gupta *et al.* 2008, Bulygina and Gupta 2009, Kumar 2011, Montanari and Koutsoyiannis 2012). The near future will bring to our community impressive opportunities related to new monitoring and measurement techniques and, as such, new research questions will emerge on the use of the related information (Gupta *et al.* 2008, 2012, Kumar 2011, S. Grimaldi IAHS Blog, K. Beven IAHS Blog, D. Post IAHS Blog). How can we initiate the development of new measurement techniques? What is technically possible? What opportunities do we have to reduce the current uncertainty of observations (McMillan *et al.* 2012)? Indeed, new observations will bring new insights, but we are still challenged about how to integrate different types of information or identify disinformative data (Beven *et al.* 2011). It is therefore urgent to proactively devise new monitoring strategies (R. Hut IAHS Blog, V. Smakhtin IAHS Blog, G. Di Baldassarre IAHS Blog), as well as to develop new techniques to efficiently turn the raw data streams into useful information and ultimately new knowledge (Gupta *et al.* 2008, S. Moges IAHS Blog, G. Mahé IAHS Blog).

In fact, the massive growth in the availability of remotely sensed data is likely to significantly change modelling approaches, given the possibility to more directly observe the various constituent variables of the water balance (e.g. precipitation, evaporation, snow and ice, soil moisture, and terrestrial water storage variations). Indeed, remote sensing is a primary source of observations of land surface hydrological fluxes and state variables, particularly in regions where *in situ* networks are sparse (e.g. to reconstruct hydrographs in data-poor environments, Callow and Boggs 2013). Over the last 10 years, the study of land surface hydrology using remote sensing techniques has advanced greatly with the launch of NASA's Earth Observing System (EOS) and other research satellite platforms, and with the development of more sophisticated retrieval algorithms (e.g. Reichle *et al.* 2002, Schumann *et al.* 2009, Donnelly *et al.* 2013).

Interesting perspectives are also provided by the use of digital cameras and cell phone signals to retrieve rainfall intensity and other hydrologically relevant information (Overeem *et al.* 2011, 2013, Parajka *et al.* 2012). There are many more examples of emerging monitoring technologies, such as distributed temperature sensing systems (DTS), new tracers and so forth (Selker *et al.* 2006, Stewart *et al.* 2012, Tauro *et al.* 2012).

The future is also creating new relevance for traditional monitoring methods. The availability of modern technologies should not undermine the efforts that must continuously be made to maintain and strengthen current monitoring networks. In particular, river discharge remains the most important variable to close the hydrological balance and to set water resources management policies: it is hoped that modern technologies will allow some reduction in the uncertainty associated with its direct measurement (Song *et al.* 2012, Whitfield *et al.* 2012).

It is worth noting that, in some parts of the world, investment in monitoring networks is decreasing: especially in the developing world, but also in developed countries that are affected by social, economic and political changes (Harmancioglu *et al.* 2003). Thus, the scientific community needs to clearly highlight the importance of monitoring networks and the development of long-term data sets to avoid the decline of hydrological information, and also to provide indications as to how to prioritize the installation and maintenance of measuring systems in the face of resource constraints (Lovett *et al.* 2007).

Innovative ideas are also being proposed to extract information from raw data (Babovic 2005). There are many signatures in the observations that are still to be explored (Gupta *et al.* 2008, Neal *et al.* 2011, Wagener and Montanari 2011, Toth 2013, H. McMillan IAHS Blog, P. Troch IAHS Blog). The future of hydrology will certainly rely, more than in the past, on exploiting new information from historical data (see Brázdil and Kundzewicz 2006, and the other articles of the special issue of the *Hydrological Sciences Journal* on historical hydrology, HSJ 2006; see also Elshorbagy *et al.* 2000, Gupta *et al.* 2008, Koutsoyiannis *et al.* 2009a, Arheimer *et al.* 2011a).

Data-driven modelling techniques (See *et al.* 2007, Abrahart *et al.* 2012, Young 2013, E. Toth IAHS Blog) may help us to understand the value and the limitations of what data can tell us, for example their salience as input variables or their informative content for calibration purposes. In addition, such models are powerful mergers of information, able to handle any kind of data, derived from different sources and expressed in different manners (including also soft and proxy data) and may therefore easily incorporate the measurements derived from new technologies. Hydrology will likely move from local analysis to multiple-scale assessment of information. Virtual laboratories are emerging as an interesting opportunity to store and learn from large data sets; they set standards for the retrieval and central storage of data (U. Ehret IAHS Blog), thereby providing an improved basis for model calibration and evaluation (Hipsey and Arheimer 2013, C. Perrin IAHS Blog). They also offer an excellent opportunity for carrying out comparative studies on multiple catchments (Arheimer *et al.* 2011b, E. Boegh IAHS Blog, P. Gentine IAHS Blog, M. Sivapalan IAHS Blog) and data analysis in general (E. Toth IAHS Blog). The widespread use of technological instruments and communication systems will substantially increase the potential for "citizen science" initiatives (Buytaert *et al.* 2012), facilitating a bottom-up information flow, i.e. crowdsourcing data (not just hydrological data but also "unstructured data") from non-experts that help us understand the interface of humans with the environment/water cycle. Knowledge flows will be aided by emerging innovations in visualization technologies that can be used to communicate complex scientific information within diverse research teams, as well as to stakeholders and to the general public (Tidwell and Van Den Brink 2008, White *et al.* 2008, Waser *et al.* 2010, Neal *et al.* 2011, Buytaert *et al.* 2012).

Finally, the increased availability of communication means will provide invaluable opportunities for cooperation. Whilst past research in hydrology has been largely conducted individually or within research groups, cooperation will become widespread in the future, therefore ensuring the exchange of ideas and opportunities (including funding). Cooperation will drive significant changes in research practice and will definitely be an important opportunity for pursuing interdisciplinarity, which is recognized as an essential prerequisite for the synthesis of the major research activity that is being developed.

In summary, the next 10 years will bring impressive opportunities for research in hydrology, paving the way for new scientific approaches and modelling techniques. Therefore, devising a research agenda for the next decade requires a vision of what the future will bring in terms of new measurements and new opportunities. A fresh perspective is needed to effectively drive the community effort to address the research challenges related to the analysis and modelling of changing hydrological systems.

HYDROLOGY: A SCIENCE PROJECTED INTO THE FUTURE

IAHS research initiatives play a leading role in coordinating the efforts of the hydrological community. They provide input for education, and motivation to young researchers to further develop and round-out their background, and shape their research experiences. To effectively achieve their purpose, IAHS initiatives are inspired by the long history of hydrology and are forward-looking to its evolution in connection with emerging technical and research challenges. Their function is to project the legacy of hydrology into the future with continuity, by taking advantage of the best from human and technical resources. This section of the paper presents a brief history of hydrology and considers its future, explaining the rationale for the need to focus on hydrological change and its implications for society.

Hydrology has a long history (Biswas 1970, UNESCO-WMO-IAHS 1974). Ancient populations developed along the banks of lakes and rivers. In order to ensure water supply for irrigation and civil use, measurements were taken to better understand water dynamics. River levels of the Nile were observed by the Egyptians four millennia ago (Biswas 1970, Said 1993) and water stage was gauged in the Minjiang River (tributary of the Yangtze River) for the Dujiangyan Weir 2268 years ago. Rainfall measurements were taken about 3100 years ago in the Shang Dynasty of China (*Chinese Hydrology Annals* 1997) and approximately 2400 years ago by Kautilya of India (NIH 1990).

Following the first attempts to measure precipitation and to quantify the relationship between rainfall and runoff by Perrault and Mariotte in the 17th century (Perrault 1674), the modern quantified setting of hydrology appeared around the middle of the 19th century, when, for example, Mulvaney (1851) proposed the so-called "rational formula". Hydrology was substantially developed during the 20th century, when it became a fully independent science (IAHS 2012). During the history of hydrology, scientific progress was always triggered by the need to study water security problems and to mitigate water-related risks (Klemeš 1988). In particular, during the 20th century humans developed a multi-faceted use of water through extensive agricultural development and energy production (IAHS-UNESCO 1977, Davis 1985). Redistributing water in space and time became an urgent necessity, to assure water supply, sanitation and flood mitigation.

Through intense research activity, better understanding was gained of the physics and stochastics of the water cycle, and the hydrological community increased in size world-wide. Over time, the pivotal role of hydrological processes in mediating the relationship between humans and the environment became increasingly clear. For example, land-use change studies were typically a main driver for the development of hydrological sciences in the past (e.g. Crow *et al.* 1976).

It is unquestionable that, with the current trend in societal and environmental development (Postel 2011, Sivakumar 2011, Famiglietti 2012), the variability of hydrological conditions is changing (Montanari 2012) and is endangering water uses that are essential to society, as well as affecting flood-prone settlements. Therefore, hydrology will become increasingly important in the future and will inevitably be more focused on the links and feedbacks with society due to the changes of the upper (e.g. climate) and lower (e.g. landscape, water use or transfer) boundaries that influence the components of the hydrological cycle (Ren *et al.* 2012). The more society develops, over multiple time scales, the more it impacts on hydrological processes by inducing perturbations that require unnaturally quick adaptation (and related feedback) of water systems (Falkenmark and Lannerstad 2005). For this reason, gaining an improved understanding of change is an urgent need.

In summary, hydrologists will necessarily have to focus on the mutual relationship between water and society (see Figs 2 and 3), given that hydrological processes are connected to human systems through multiple two-way interactions. Therefore, hydrological

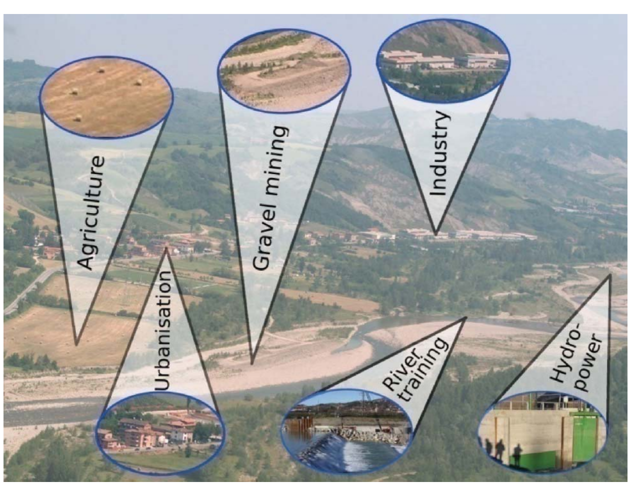

Fig. 2 Examples of interaction between environmental and human systems.

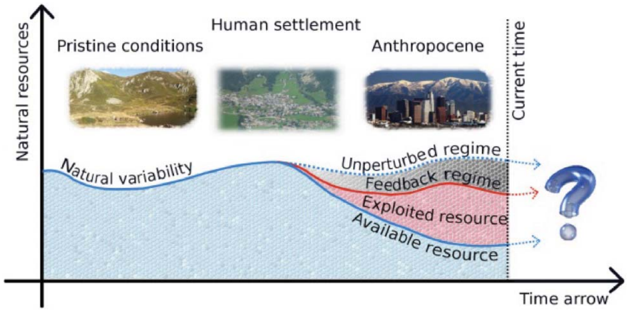

Fig. 3 Sketch of the progress of human-induced hydrological change over time.

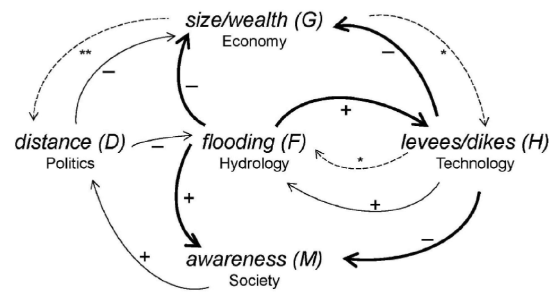

Fig. 4 (© Di Baldassarre *et al.* 2013a, reproduced from Di Baldassarre *et al.* 2013a under the CC Attribution 3.0 license) Loop diagram showing how hydrological, economic, political, technological and social processes are all interlinked and gradually (continuous thin arrows) co-evolve, while being abruptly (continuous thick arrows) altered by the sudden occurrence of flooding events. Dashed arrows indicate control mechanisms that are quantified by differential equations in Di Baldassarre *et al.* (2013a).

modelling should explicitly take these interactions into account with a description that should depart from the sequential (one-way) practice, and establish dynamic links that allow incorporation of feedbacks. The societal components that interact with hydrological systems include: technological infrastructure, institutional means, economic conditions and social behaviours.

An example of the above integration is presented in Fig. 4. In the assessment carried out by Di Baldassarre *et al.* (2013a) of the interaction between societal development and flood risk, the hydrological, societal, political, economic and technological models are given by a system of four differential equations that are linked together and jointly solved.

HYDROLOGICAL CHANGE: A WELL-KNOWN UNKNOWN

Hydrological change has been the subject of many contributions in hydrology in previous years. Several studies were stimulated by the attention that the international scientific community dedicated to climate change and its implications for water resources. However, the impact of climate change on hydrology is still unclear (Roderick and Farquhar 2002, Koutsoyiannis *et al.* 2009b, Blöschl and Montanari 2010, Sun *et al.* 2012), while the prominent role of hydrological change for society is very clear. The need to better understand hydrological change and its connection with societal changes was one of the factors that inspired the new IAHS SD.

On the one hand, it is well-known that hydrological systems are changing. Indeed, seasonality and long-term fluctuations, as well as natural variability, make the forcings of hydrological systems multifaceted and seldom repeatable. Variability is the reason why catchments are diverse and evolving systems. By facing changing pressures they assume individual behaviours and become naturally trained to face unexpected situations (Walker and Salt 2006). As water flows, it inevitably changes its surroundings by the associated transfer of energy, resulting, for example, in erosion or evaporative cooling. Spontaneous changes in systems that are not in thermodynamic equilibrium (i.e. not dead) are irreversible processes. The entropy in these processes increases in accordance with the second law of thermodynamics, a law that is crucial for the understanding of change and its cause (Kondepudi and Prigogine 1998, Atkins 2007, Kleidon and Schymanski 2008). Flow and evolution in nature, including life, are inevitably associated with increase of entropy and closely related to change.

On the other hand, change is unknown to the same extent that its driving force, entropy, is a concept closely related to uncertainty (Koutsoyiannis 2013). Natural variability is far from being completely understood and is perhaps unpredictable in deterministic terms, although it has been recognized as the driver of significant perturbations of water systems (Brandimarte *et al.* 2011, Montanari 2012). Unpredictability is strictly related to indeterminacy and uncertainty, therefore representing a relevant limitation for the practical application of hydrological sciences to management and policy development. In particular, hydrological records appear to be affected by long-term cycles that cannot be related to seasonality. These are often attributed to climatic fluctuations, but catchment feedbacks and adaptation have pivotal roles in mediating the ultimate response in catchment function, though this is still poorly understood. Furthermore, in the past few decades, increasing attention has been given to human-induced hydrological change, with several impact studies carried out through scenario analysis. Although one cannot question that human activity is having an impact on hydrological systems, it is still unclear how the related feedbacks can be deciphered and modelled. The history of human development bears witness that society evolved where water was available, often causing water degradation and threatening the sustainability of society itself. Better understanding of the mechanisms governing this loop, and the associated tipping points and thresholds, is a key step for hydrological research to ensure future sustainability of water exploitation and resilience of human and environmental systems.

Figure 3 presents a sketch of what the major challenges are to pursue the above objective. In pristine conditions, natural variability dominates and induces change in natural resources (Fig. 3, blue continuous line). After human settlement, a perturbation is induced whose feedback generally provokes a decrease of the resource that is independent of its possible exploitation (Fig. 3, red line). For instance, artificial reservoirs increase evaporation and therefore induce a corresponding reduction of the river flow volume (Destouni *et al.* 2013). Moreover, they often imply a change in groundwater recharge and, therefore, in downstream groundwater conditions. Part of the natural resource altered by this feedback is then exploited, and potentially degraded by society, thereby further reducing its availability (as indicated in the blue line after human settlement in Fig. 3). Such feedbacks and exploitation have dramatically increased in recent times (Steffen *et al.* 2011) and an initial challenging question relates to their interaction with natural variability.

While exploitation is relatively straightforward to estimate, the feedbacks—such as those triggered by reservoir impacts, or those considered in flood risk analysis, by Di Baldassarre *et al.* (2013a)—the climatic changes, the degradation of water bodies and many others, are poorly understood. Therefore, it is clear that improved understanding of these complex system-scale dynamics is needed to enable predictions to support the management of natural resources.

New coordinated research is needed to decipher and predict the connections and feedbacks between society and hydrological systems in the long term, by studying how society and hydrological processes have co-evolved throughout history and continue to do so. To this end, an interdisciplinary approach is needed, in particular with respect to interacting with the social sciences.

An improved understanding of environmental change, including climate change and hydrological change, will allow society to set priorities and mitigation policies more effectively, to ensure long-term co-existence with the environment.

PANTA RHEI: THE IAHS SCIENTIFIC DECADE 2013–2022

The focus of change in hydrology and related societal systems for the Scientific Decade 2013–2022, that was identified by the consultation process initiated by IAHS, includes the two main issues of hydrological change and hydrology and society (IAHS blog). The title the community identified for the new SD is "Panta Rhei", after the famous statement attributed to Heraclitus (Plato, *Cratylus*, 339–340). The literal translation of "panta rhei" is "everything flows", meaning that all things (and in particular water) are perpetually changing. The subtitle of the SD is "Change in hydrology and society", to indicate that the research activity should focus on their interaction and feedbacks that lead to relevant and interconnected shifts in both hydrological and societal systems.

Panta Rhei aims to bring the hydrological community together under a common umbrella to undertake pioneering research addressing the challenges of change, by enhancing the knowledge of hydrological systems as fundamental connections between humans and the environment. Panta Rhei is a global initiative. It will bring together scientists from all parts of the world, and it will also provide a global perspective, with the recognition that water problems are highly inter-connected at all scales and levels: local, river basin, regional and global. Panta Rhei is a grass-roots initiative: it is inclusive of the interests and experiences of a wide range of scientists, and has the ambition to empower people everywhere to contribute to and benefit from the ideas, work and experiences of everyone. We hope that it will eventually influence the way in which hydrology is taught (i.e. education in hydrology). Panta Rhei focuses on research activities in hydrology with an interdisciplinary approach: it will involve collaboration and interaction across the natural sciences (hydrology, geomorphology, ecology), across the divide between natural and social sciences (economics, politics, policy sciences), and between science and practice (between hydrologists and water managers and practitioners).

Fig. 5 The logo of Panta Rhei. It recalls the colour and shape of the IAHS logo, as well as the connections between the catchment, water and society.

The logo of Panta Rhei is shown in Fig. 5. The Science Plan, which was shaped and refined with an unprecedented concerted community effort and synthesis (see Introduction), is available for download at the IAHS web site (www.iahs.info).

Concepts of Panta Rhei

The main concepts of the scientific activity being developed in Panta Rhei can be summarized in the following statements:

- The interaction between hydrology and society is changing, generating new connections and, in particular, more significant feedbacks which need to be understood, assessed, modelled and predicted by adopting an interdisciplinary approach. Humans are an important part of the system: there is a need to study the two-way coupling between humans and nature (socio-hydrology) within a more comprehensive framework.
- Co-evolution of hydrological and connected systems (including society) needs to be recognized and modelled with a suitable approach, in order to predict their reaction to change. The feedbacks between hydrological processes, catchment structure, society and ecosystems provide important information on catchment functioning (Figs 1 and 6).
- Hydrological processes determine the relationship between environment and humans (by determining, among others, water-related risks and water security). Hydrological change is vital to society, as well as to the environment itself.
- Change results from the superimposition of natural variability and human-induced effects.

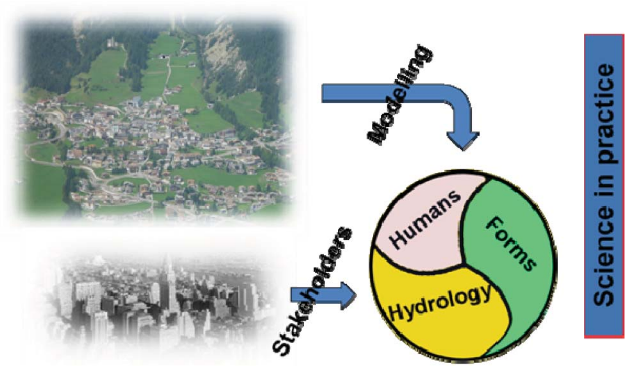

Fig. 6 Co-evolution of hydrological systems with society and catchment forms.

Understanding their interaction is critical for deciphering the feedbacks on the environment and hydrological systems.

- Advances in hydrology are currently limited by the available measurement techniques. The community should therefore be proactive in devising innovative monitoring strategies by taking advantage of new technologies and new generations of data.
- Future science must necessarily be based upon an interdisciplinary approach.

There is a final and very important premise, identified by the community, for the success of Panta Rhei that is more philosophical than scientific. The research challenges for hydrology in the next 10 years should be tackled through a collective effort, thus emphasizing the key role that scientific associations like IAHS must play. Cooperation among researchers through science initiatives, exchange programmes and virtual laboratories is fundamental for the on-going success of hydrological science, as well as the education and growth of the community. Hydrology must be dealt with by using collective and inclusive discussion and cooperation, while preserving the value of individual ideas and contributions. There are many countries in the world whose hydrological features are poorly known and the SD can contribute to fill this knowledge gap (Viglione *et al.* IAHS Blog) and to strengthen scientific expertise in areas that have potential in terms of research contribution and community building.

Targets of the research activity

Hydrology is a science that is deeply rooted in its prestigious history and has a bright future, which opens exciting perspectives to bridge past developments with new opportunities. Awareness of the critical importance of building on the past led the community to devise the targets of Panta Rhei, by adopting three clear objectives that are, at the same time, classical and innovative when projected into the future.

Target 1: Understanding Understanding has always been the essence of hydrology as a science. Improving our knowledge of hydrological systems and their responses to changing environmental (including anthropomorphic) conditions, and in particular variability and indeterminacy, is a key step in deciphering change and the interaction with society. Within Panta Rhei, understanding will be pursued with an interdisciplinary approach to gain improved knowledge of the interactions and feedbacks with connected systems, with particular emphasis on society. Special attention is to be devoted to complex geographic systems, such as mountain areas, urban areas, alluvial fans, deltas, intensive agricultural areas, and to the specification of new measurement and data analysis techniques that will allow the development of new understanding.

Target 2: Estimation and prediction Estimation and prediction are closely related to understanding, and are the essence of hydrological engineering and hydrological applications, embracing flood-risk mitigation and water resources management. Target 2 includes estimation of design variables under change and uncertainty assessment, a crucial step to support risk evaluation. The interdisciplinary focus of Panta Rhei will contribute to an improved understanding of the interactions between several uncertainty sources (for instance, uncertainties related to societal development) to better inform predictions.

Target 3: Science in practice This signifies that Panta Rhei aims to include societal relevance in the study of hydrological systems and, therefore, aims for iterative exchange between science, technology and society. Science in practice includes policy-making and implementation. The fact that hydrology is relevant to society implies the identification of the needs of various water users, as well as the threats that water poses in terms of floods, land degradation and droughts. More than in the past, we need to focus on equities between demand- and supply-driven activities.

Panta Rhei recognizes the feedbacks between each of the three targets: improved understanding may potentially lead to more accurate predictions, which

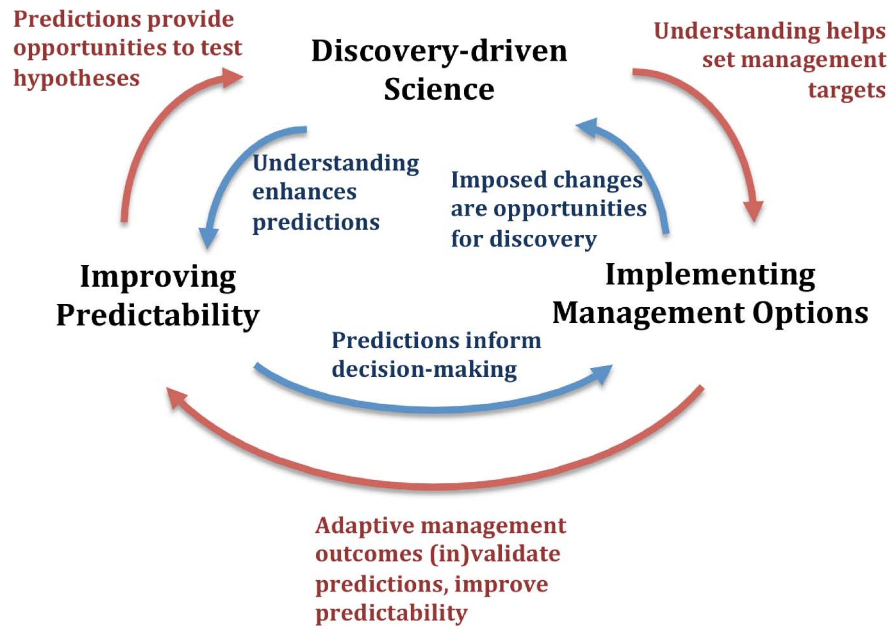

Fig. 7 (© Thompson *et al*. 2013, reproduced from Thompson *et al*. 2013 under the CC Attribution 3.0 license) Interactions among the targets of Panta Rhei.

helps sustainable management. Figure 7 summarizes the interactions between the targets of Panta Rhei.

Science questions

The study of change in hydrological systems and society implies fundamental science questions. In Panta Rhei, these are deliberately few and concise, and have been formulated after specific consultation with the science community through the IAHS blog and milestone meetings. Most science questions address more than one target, or cut across all:

Science question 1 (SQ1, Target 1) What are the key gaps in our understanding of hydrological change?

Science question 2 (SQ2, cross-cutting) How do changes in hydrological systems interact with, and feedback to, natural and social systems driven by hydrological processes?

Science question 3 (SQ3, cross-cutting) What are the boundaries of coupled hydrological and societal systems? What are the external drivers and internal system properties of change? How can boundary conditions be defined for the future?

Science question 4 (SQ4, targets 2 and 3) How can we use improved knowledge of coupled hydrological–social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability?

Science question 5 (SQ5, cross-cutting) How can we advance our monitoring and data analysis capabilities to predict and manage hydrological change?

Science question 6 (SQ6, Target 3) How can we support societies to adapt to changing conditions by considering the uncertainties and feedbacks between natural and human-induced hydrological changes?

The science questions of Panta Rhei are both rooted in the fundamental concepts of hydrology and focused on society and environmental management. They propose a compelling synthesis between basic and applied research. *Panta Rhei focuses on science for society.*

Enabling research

The research activity in Panta Rhei will focus on water problems in a changing environment. Therefore, Panta Rhei is a hydrological research initiative considering observations, models and interdisciplinary partnerships for changing systems (see Fig. 8). The deeper collaboration between scientists, engineers and managers will raise new kinds of questions and new methods. Panta Rhei will be inclusive and interdisciplinary, to favour global

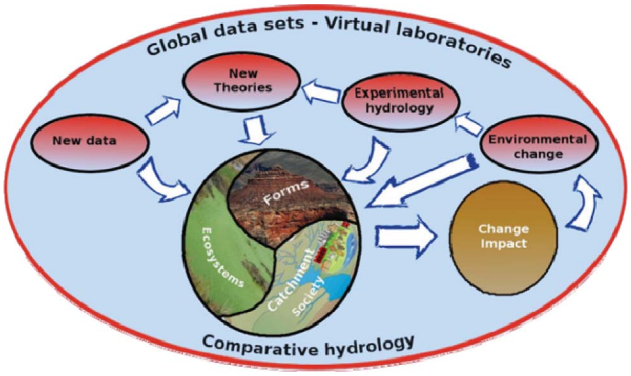

Fig. 8 Enabling research in Panta Rhei.

involvement and cohesion of the hydrological community, as well as the exchange of experiences with sister disciplines, in particular the social sciences. The activity will be driven by the science questions and focused on the targets, within a flexible implementation plan to include any research that is relevant to hydrology and society.

The activities related to SQ1, SQ2 and SQ3 should enable us to better understand hydrological systems in their entirety. To gain an interpretation of hydrological change and to understand the implications for related sciences, we need improved understanding of the internal dynamics of hydrological processes and how they connect to related systems.

Examples of related activities include (but are not limited to):

- developing new measurement techniques to constrain uncertainty in closure of the mass balance that is fundamental to improved process understanding;
- theoretical and experimental analysis of hydrological processes and their links with and feedbacks to connected systems, assessment of their behavioural determinants, intrinsic dynamics and indeterminacy;
- climate and land-use impact studies conducted with a bottom-up approach, namely, by focusing on the resilience of hydrological systems to change, either natural or human-induced;
- theoretical and experimental comprehensive analyses of the impacts and feedbacks of human activity on the dynamics of connected hydrological systems;
- analysis of the co-evolution of hydrological processes and catchment signatures, ecosystems and social systems;
- analysis of the scaling properties of hydrological processes and their long-term patterns;
- reconstruction of past conditions and climate (historical hydrology);
- new modelling philosophies and approaches for hydrological systems in close connection with human activities; and
- entropy modelling and evolution of natural systems.

Special focus is given by SQ2 to assessing the impact and feedbacks of environmental changes on society, which is essential to decipher the extent of human influence and to set priorities for mitigation policies. The reaction of society to change is necessarily related to its causes and therefore an informed quantification is needed. Activities may include:

- coupled modelling of environmental and human systems (socio-hydrology interactions and feedback processes);
- integrated water resources management and economics; and
- comparative analysis of hydrological systems to better understand the reaction of hydrological processes to different perturbations in different environments, and to learn from the similarities and differences of different places.

Science question 4 concentrates on the improvement of hydrological predictions, by gaining a better understanding of the related processes with a particular focus on indeterminacy, namely, the occurrence of randomness that prevents the implementation of a fully deterministic description. Randomness may be an intrinsic property of hydrological processes, as well as of socio-economic developments. However, a random description may be an alternative to a deterministic one, even in the presence of epistemic uncertainty (which is related to a lack of knowledge or limited computational capacity or monitoring means). Activities may include:

- development of theoretical schemes for the integrated modelling of hydrological knowledge and hydrological uncertainty (Beven 2008);
- setting up strategies for estimating and communicating uncertainty, and solutions for reducing decision-making and operational uncertainty;
- use of advanced monitoring techniques for reducing data errors; and
- development of advanced prediction methods in the presence of indeterminacy.

Science question 5 focuses attention on recent technological developments, which offer opportunities for improved hydrological monitoring. They will greatly affect hydrological modelling. Examples of activities are:

- proactive research on opportunities conveyed by advanced monitoring methods;
- enhanced use of remote sensing for water resources estimation and management;
- integration of advanced information into hydrological models, through development of increasingly sophisticated data assimilation approaches (model–data fusion);
- development of advanced monitoring techniques for deciphering the interaction between hydrological processes and human settlements and activities; and
- linking new observations and techniques with historical data sets.

Science question 6 demands a holistic view of human-induced loads and unknown loading capacities. Here, the role of thresholds and abrupt changes has to be analysed. Examples of activities are:

- identification of hot-spots of human vulnerabilities under on-going hydrological changes;
- estimation of thresholds of hydrological loading capacities where overtopping would affect the societies, as well as nature, in an unbearable way (Kwadijk *et al.* 2010);
- raising public awareness of human-induced changes in hydrological conditions;
- transboundary water resources management, and water conflicts; and
- impact of large-scale water structures and large-scale water transfer.

The above research topics open several exciting avenues for research, revisiting classical hydrological theory by proposing new approaches and possibly new concepts. Practical examples could be the incorporation of population dynamics in groundwater modelling and rainfall–runoff modelling. If working within a stochastic setting, such an approach may imply embedding a non-stationary input variable, thus producing a non-stationary output. Another example could be the incorporation of human dynamics when modelling groundwater–surface water interaction, thus accounting for e.g. artificial water storage and water withdrawal.

The above-mentioned enabling research represents a first example, which will be continuously updated to reflect the development of the Panta Rhei interests, as well as on-going international research trends. The scientific research of Panta Rhei will link with the main international research organizations to ensure full connection with the global hydrological community.

Implications for hydrology education

The ideas and results of Panta Rhei can be readily implemented in education. There are already significant examples of the concept of hydrological change being taught in degree and doctoral programmes (Blöschl *et al.* 2012, Seibert and Vis 2012; see also the special issue of *Hydrology and Earth System Sciences*, HESS 2012, which identifies other examples). Accounting for the human forcing in hydrological analysis is the basic concept to be able to incorporate feedbacks with society. It implies the incorporation of societal processes in the constitutive relationship of hydrological models, when technically and scientifically feasible. From an educational point of view, the idea is simple and practical examples can be made easily. For instance, one may adapt basic hydrological models to account for human water withdrawal from rivers, starting from solutions that are currently applied and then moving forward by improving feedback modelling. By introducing simple modifications, students would more easily be able to comprehend the complexities of an evolving environment.

Implications for operational hydrology and management

Knowledge transfer is essential to connect science with society. Panta Rhei will place emphasis on transferring science development into practice through encouraging the direct involvement of policy makers, operational services and research institutes in the scientific work and discussion. There is a long and well-established tradition of cooperation in hydrology, and within IAHS in particular, between researchers and practitioners, which derives from addressing real-world water issues. Panta Rhei will continue this tradition by reinforcing the connections with governmental and non-governmental organizations, water managers and local administrations. Moreover, Panta Rhei will set the basis for seeking improved connections with national and international funding agencies.

Interdisciplinarity

According to the vision of the IAHS community, Panta Rhei is a research initiative in hydrology to gain an improved understanding of water processes and to contribute to the solution of water problems. Within this framework, interdisciplinarity is seen as a necessary prerequisite to study the dynamic links between hydrological and connected systems. Interdisciplinarity will be sought primarily with social sciences, but also with geosciences in general, statistics, numerical computing and information technology.

It is well known that interdisciplinarity is an ambitious purpose in science. The international scientific community is currently divided into several separate fields, each one editing its own journals, organizing its own workshops and symposia, and individually recognizing the value of its research. Such organization does not automatically promote better interaction among sister disciplines; therefore, science initiatives like Panta Rhei can play a relevant role in attempting to encourage cross-cutting research.

Panta Rhei will consider interdisciplinarity as an integration instrument in order to relate various fields of disciplinary knowledge, with the basic goal to obtain a synthesis of knowledge, theory, concepts and methods (Schmidt 2008). Interdisciplinarity will be sought in Panta Rhei by establishing links with scientists working on water issues from a different perspective to hydrology. In particular, the following actions will be promoted:

- identification of joint research themes;
- collaboration on joint workshops, symposia and editorial initiatives; and
- activation of initiatives within the hydrological community to promote and recognize interdisciplinary research efforts, by involving journal editors and promoting interdisciplinary research projects.

Achieving interdisciplinarity will be a measure of the success of Panta Rhei and will be discussed and evaluated throughout the SD.

Scientific innovation

As introduced above, Panta Rhei is a community initiative focusing on hydrological and societal systems. The related research fields are already well known and popular among hydrologists, as the numerous contributions already published in the literature clearly demonstrate (UN-Water 2012, Hrachowitz *et al.* 2013).

Panta Rhei aims to act as a catalyst by pursuing an innovative approach, whose distinctive behaviours are:

(a) to include human activity as an integral dimension of hydrological science, giving the opportunity to shift the focus from pristine catchments to human-impacted environments; and
(b) to derive general findings, thus supporting the development of results of general validity from the numerous case studies that the community is working on.

Item (a) above will be pursued by seeking a more comprehensive representation of the links and feedbacks between hydrological and human systems, to gain an improved understanding of their structure and interaction through time. An assessment of the strengths and significance of these links will be necessary to guide model development and, in particular, the level of detail with which the interactions should be simulated. Advanced techniques may include unified models of hydrological and significant societal forcings, with contextual estimation of the related parameters (Di Baldassarre *et al.* 2013a). To be most useful for solving real-world water problems, such a framework should be preceded by a careful assessment of its technical feasibility and its appropriateness in view of the spatial and temporal scales that are involved, and the unavoidable increase in complexity and therefore indeterminacy and uncertainty. In some cases treating the human impact as a boundary condition or external forcing, as traditionally done, may be more practical, but in other cases representing the two-way feedbacks in a dynamic way will be essential. Improving the understanding and representation of the above links will allow generalizations of the processes (item (b) above), going beyond the traditional case study perspective.

Achieving the above goals of scientific innovation will require a deeper integration between hydrological and social sciences, so that the societal component of hydrological models can be formulated within an advanced and targeted framework to address water problems for people.

IMPLEMENTATION PLAN

Panta Rhei, like PUB, has been designed as a grass-roots initiative that will reflect the diverse interests of hydrologists. The purpose is to involve scientists world-wide to achieve the stated objectives through research, educational and outreach activities. Therefore, the international community will be the main actor of Panta Rhei, within a flexible operational framework. Panta Rhei adopts the view that a plurality of interdisciplinary approaches should be pursued to account for the diversity in research practices and hydrological behaviours across the continents. The IAHS role will be to coordinate and facilitate the research of the hydrological community towards achieving the Panta Rhei targets consistent with the fundamental objectives of the IAHS.

Given the above guiding concepts, the proposed structure for Panta Rhei research activities aims to foster a flexible, self-organizing framework which will:

- be inclusive of the diverse range of research interests and a similarly wide range of applications;
- encourage the integration of different areas of expertise towards specific common objectives and targeted setting of the research themes and working groups;
- emphasize the merging or assimilation of theoretical advances, process understanding, new data acquisition and archiving technologies, and comparative analysis; and
- seek an improved connection between science and practice.

Panta Rhei activity will be centred on research themes and working groups that will be identified through consultation with the hydrological community, with particular attention given to interdisciplinarity.

CONCLUSION

The new Scientific Decade of IAHS 2013–2022, Panta Rhei, focuses on hydrology for society and related changes. Panta Rhei will be the leading motif of IAHS in the next 10 years, including environmental feedbacks and humans as an essential part of hydrological systems. Panta Rhei is a challenging initiative that is rooted in the history and tradition of hydrology. It will promote a paradigm shift and a re-organization of the way in which hydrology is studied, taught and applied. It is a research initiative in hydrology that will adopt an interdisciplinary approach to address problems that can only be solved through community efforts at all levels. Interdisciplinarity will be sought by involving scientists working in sister disciplines (specifically the social sciences) in the Panta Rhei activities, and by organizing specific workshops, symposia and joint editorial activities that address these issues.

Panta Rhei will be a scientific, grass-roots initiative that will provide a forum to share ideas, to target common objectives and to disseminate awareness and results. It will be developed through an enhanced network of hydrological research groups all over the world, and an improved global accessibility to scientific research. Panta Rhei will be more than science, in that it will include outreach, educational and technological activities, as well as initiatives targeting the awareness of practitioners, water resource engineers, public administrators and funding agencies.

Panta Rhei will bring to the world an innovative scientific message from IAHS: hydrological systems are the interface between the environment and human needs for water, and understanding hydrological change is the key to planning sustainable water exploitation and managing water supply for drinking, for sanitation, for food, for energy production and for societal development. Panta Rhei will provide an improved framework to address the global water crisis, and will be the message of the international hydrological community to the world for the decade 2013–2022. It will be an exciting and collective journey to explore the possibilities and opportunities that exist for deciphering and representing the dynamic links and feedbacks between hydrology and society, for the sake of providing innovative findings on water for people.

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would not have efficiently reflected the many different and constructive views of hydrologists world-wide.

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