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SCIENCE PLAN FOR THE DECADE 2013-2022

Panta Rhei – Everything flows

Change in Hydrology and Society

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and Society*

Prepared by:

IAHS Task Force on the Scientific Decade 2013-2022
(Alberto Montanari – Chair)

Revised by:
G. Young, H.H.G. Savenije, C. Cudennec, D. Koutsoyiannis, M. Sivapalan, D. Hughes, T. Wagener, L. L. Ren, S. Grimaldi, G. Blöschl, K. Beven, H. Gupta, B. Arheimer, Y. Huang, A. Schumann, D. Post, V. Srinivasan, E. Boegh, P. Hubert, C. Harman, S. Thompson, M. Rogger, M. Hipsey, E. Toth, A. Viglione, G. Di Baldassarre, B. Schaefli, H. McMillan, S.J. Schymanski, G. Characklis, B. Yu, Z. Pang, V. Belyaev

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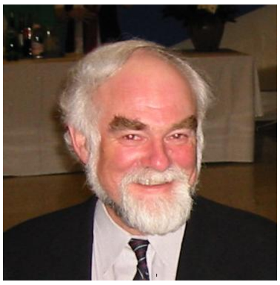

We live in a highly dynamic world with many changes occurring simultaneously. Some of these changes are the result of natural forces and some are human-induced. Some are relatively slow and some are sudden. Some are predictable and others unexpected and take us by surprise.

Landscapes and topography evolve in conjunction with the evolution of ecosystems. Many of the processes of denudation and erosion and those of sedimentation are slow and persistent and to a large extent predictable; some such as earthquakes and volcanic eruptions may be sudden, catastrophic and largely unpredictable. Climate, too, may exhibit both longer and shorter trends and cycles of change, sometimes suddenly influenced by, for example, changes in sunspot activity or massive volcanic eruptions quickly changing energy inputs and perhaps inducing changes in intensity and occurrence of precipitation.

Human activity is also changing. First and foremost human populations have grown enormously – from 1 billion inhabitants some 200 years ago to over 7 billion at the present day; and the acceleration of overall growth in the past few decades has been remarkable. However such simple statements give only half of the story for, while much of the less developed world is experiencing unprecedented population increases, other countries and regions such as Eastern Europe are witnessing significant declines in population. Further, there are very significant movements of population within countries, especially towards cities and, in many instances, such movements result in social disruption.

As globalization takes place and as advances in communication make our world ever more integrated and fast to respond to fiscal and economic crises, so we can, in highly unpredictable fashion, find ourselves at the mercy of such economic catastrophes that beset us in 2008-09. Such sudden changes can have far-reaching world-wide political and economic consequences.

Political set-ups are also in process of almost constant change. Some countries break up into smaller units while others merge into larger groupings. New trading blocks appear affecting interactions between countries while, at the same time, internal political restructuring may be taking place affecting not only internal trade and economic growth but also affecting interactions between countries. And, unfortunately, in the worst of circumstances internal political disruptions may lead to civil unrest with sometimes dire consequences.

Such are the broad contexts within which we must consider hydrology and water resources management.

Hydrology is changing as results of both natural and human-induced changes. The climatic drivers of hydrological processes have been changing as a result of cycles and trends with durations over short to very long time periods. Until the last century or so such changes have been ‘natural’; however to an ever greater degree over the last few decades human influences on climate have been increasing leading to changes in energy inputs to the earth’s surface and probably influencing the location, duration and intensity of precipitation. Changes have been particularly evident in high latitude and high altitude locations where processes of snow and ice melt have been greatly affected with consequences for the regimes of many river systems.

In addition, and possibly more important than climate changes, have been the effects of human-induced changes to land cover, the construction of dams and diversions and the mining of groundwater resources. The depletion of forests, the increases in farm land and the growth of human settlements have been some of the more important elements of change greatly affecting runoff regimes. The proliferation of dams and diversions are having enormous consequences – changing the probability of floods, having great impact on sediment transport and deposition and in general affecting the availability of water in quantity and quality for the many uses to which the resource is put – and affecting, also the natural ecosystems on which humans ultimately depend. The mining of groundwater resources is becoming a particularly important consideration in those many locations and regions in which groundwater is of paramount importance as a source of supply.

The management of the resource is becoming more and more difficult in those many regions in which the supply of water is being outstripped by demand and where the threats posed by water are becoming increasingly greater. The resource is used for many purposes – for the basic human needs of food production and for health; for the production of energy and for the needs of industries – and for the sustenance of the ecosystems on which all life depends. As more and more human settlements are being located in flood-prone areas, as populations grow and as the occurrence, duration and intensity of floods increase, so the threats of flooding in terms of human life and livelihoods also increase. Low-lying coastal situations (in which there is a particular tendency for humans to settle) are becoming especially susceptible to flooding from both land and the oceans as sea levels rise.

Thus, our community of hydrological researchers has a challenging assignment to design and implement a science plan for work over the decade 2013-2022. Not only must we consider on which elements of the large number of hydrological processes to focus our attention, but we must equally consider which of those processes have most to bear on answering the challenges to society – and those challenges will be different according to the diversity of hydrological and social circumstances.

These imperatives are taken up within the science plan by focusing on three Targets:

Target 1 – Understanding, to improve the knowledge and understanding of hydrological systems;

Target 2 – Estimation and prediction, to estimate and predict the behaviours and patterns of hydrological systems, with uncertainty assessment to support risk evaluation;

Target 3 – Science in practice, to address societal needs, policy making and implementation.

The science plan for action and implementation is developed to address these targets. We can look forward to a most rewarding decade of hydrological research that will both invigorate the research community while addressing the needs of society.

Gordon Young

President – International Association of Hydrological Sciences

2. Background

The International Association of Hydrological Sciences (IAHS) was established in 1922 and has over 5400 individual members around the world. One of the missions of IAHS is to advance the science of hydrology for the benefit of society, with particular emphasis on countries that suffer from water problems. IAHS has a long and well-known track record in undertaking a range of activities that improve hydrologic knowledge and practice globally (www.iahs.info; IAHS, 2012) to enable science to serve society.

Predictions in Ungauged Basins (PUB) is the most recent initiative of the IAHS, a celebrated policy-relevant science initiative that started in 2003 and produced a significant output in terms of community building and scientific deliverables. PUB ended in 2012. A summary book has been published by Cambridge University Press in 2013 (Blöschl et al., 2013) along with a companion book on “Putting PUB into Practice” (Pomeroy et al., 2013) and a summary paper on PUB (Hrachowitz et al., 2013). The enthusiastic interest that the worldwide hydrological community dedicated to PUB clearly proves that the IAHS research initiatives play a leading role in shaping the evolution of hydrological sciences. One of the reasons for such interest certainly is the ‘grand-scale’ of challenges IAHS decades are tackling, which demand improved science networks and collaboration over geo-political and disciplinary boundaries (Ostrom, 2009). PUB demonstrated that the community was engaged by the idea of joining research efforts to identify and address an 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 witnesses the leading role that IAHS science initiatives play for hydrologists all over the world and therefore suggests the opportunity for IAHS to keep this leading role by proposing a new decadal initiative to be started in 2013, during the IAHS General Assembly to be held in Göteborg, Sweden. The IUGG General Assembly, Melbourne, Australia, 27 June – 8 July 2011, hosted a very effective debate on a potential new scientific initiative to take IAHS into the future. The expectation was that it should be similar to PUB. The above debate involved a large across-section of the IAHS officers and members. As a result, the IAHS Bureau created a new Task Force, with the mandate to prepare the Science Plan for the new initiative.

An effective debate was engaged with the International Community of Hydrologists through a blog (http://distart119.ing.unibo.it/iahs) and physical meetings that took place: in Vienna, Austria, during the General Assembly of the European Geosciences Union, in April 2012; in Nanjing, China, at Hohai University, in May 2012; in Tunis, Tunisia, during the IAHS – STAHY International Workshop on Statistical Methods for Hydrology and Water Resources Management, in October 2012; in Delft, The Netherlands, during the Celebration of the 90th Anniversary of IAHS, in October 2012; in many other locations during National and International Conferences. The blog received about 15000 visits and 54 comments and will remain open to serve as a virtual desktop for collecting community suggestions and feedbacks. Furthermore, an effective cooperation was undertaken with the IAHS Bureau to distil blog inputs and comments received from the worldwide IAHS community.

The interest in the above consultation process 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 were favoured by modern communication technologies and promoted a new spirit of global inclusivity. Every statement of this worldwide discussion was taken into account in shaping the Science Plan of the Scientific Decade 2013-2022, which is the product of an effective bottom-up process. The consultation already provided a lesson, in coherence with the vocation 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*.

Despite the profound complexity of the IAHS community, and the very diverse environments where hydrology takes place and, consequently, on which hydrologists work, some impressively well-defined and shared ideas were suggested. Such common vision testifies that the IAHS community is coherent and capable of producing an agreed strategy to tackle the diversity of technical and scientific challenges related to water cycle all around the world. **This common vision focuses on environmental changes and aims 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 concept implies a focus on **hydrology as a changing interface between environment and society through water**, whose dynamics is essential for the impact of environmental change on society. In a changing environment and changing society it is now essential to consider hydrology as a moving mechanism which is itself adapting.

The above goal is indeed ambitious as it presupposes moving forward from the assumption of static hydrological system, with the purpose of improving predictions for future water resources availability, temporal and spatial distribution, quality and demand, in a context that is characterized by increasing monitoring and computing means.

The identification of common science targets and questions for the next 10 years will provide an exceptionally significant opportunity to strengthen the role of hydrological sciences in society and to profit from the immense knowledge of the IAHS community for solving the current and future challenges related to water resources.

3. Introduction

It is widely acknowledged by researchers and governmental agencies that one of the major challenges for society in the near future will be freshwater availability, which involves an accurate investigation of the links and feedbacks between hydrology and society (Sivapalan et al., 2011), therefore focusing on water resources management and related ethical issues, (see Falkenmark and Folke, 2002), water quality 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.

In many parts of the world, poor distribution of freshwater in relation to demand is already the cause of water scarcity, which may be exacerbated by climate change (Kundzewicz 2007; Blöschl and Montanari 2010) and environmental change in general (Figure 1 and 2). The general and rapid increase of the socio-economic level in many countries is beneficial for the health of people on the one hand, but on the other hand the effect of human activities on the water cycle is deepening and widening rapidly across the planet. It is clear that water is becoming a major limiting factor to sustainable development of society (Shiklomanov and Rodda, 2003; Cudennec et al., 2007; Kundzewicz et al., 2008; Koutsoyiannis et al., 2009; Koutsoyiannis, 2011; European Environmental Agency, 2012; OECD, 2012) and, consequently, society is conditioning hydrology in many countries at a tremendous rate (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). Despite the stronger dependence of society on water, the perception of people towards 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 the social contact with natural water systems is lost, along with the individual capability to assess their state. In such a situation one may tend to assume that water is not a personal problem and therefore a paradox is induced that the hydrological community is called to solve, by further evolving water resources awareness and management in the future (Rahaman and Varis, 2005).

We live in a highly dynamic world with many changes occurring simultaneously. As far as the environment is concerned, 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 one. Human-induced changes occur largely because of population increase, the widespread increase in income, and the level of economic activity in many countries (WWAP, 2012). Global population growth is perhaps the most compelling reason for concern (Fischer et al., 1997; Koutsoyiannis et al., 2009). There is a remarkable increase of population in less developed countries while other countries (like Russia and those of Eastern Europe) are experiencing population decreases (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 having 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 more demand for food, electricity and industrial uses and hence more demand on water (Golubel 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 Soviet Union and the creation of the European Union triggered population movements from Eastern to Western European countries, and also gave rise to new institutions and new legislation that had direct or indirect influences on water management. Such developments have a relevant impact on transboundary water resources management (Kliot et al., 2001).

The societal impact on hydrology is also driven by increased demands for energy (King and Webber 2008; Koutsoyiannis et al., 2009b; Koutsoyiannis, 2011), water (Jackson et al., 2001), food (Vörösmarty et al., 2000) and living space (Zhao et al., 2001). Cumulatively, these demands result in increased human exploitation of water resources, significant modification of landscapes, and a strong human imprint on water cycle dynamics from local to global scales (Falkenmark and Lannerstad 2005; Röckstrom et al., 2009; Vörösmarty et al., 2010).

The combination of increased demand, projected changes in the frequency and severity of hydrological hazards such as floods and droughts, and on-going uncertainty regarding future climate change, means that the world faces a sharp decline in water security (Postel and Wolf 2001), which is likely to be most severe in the least resilient nations and geopolitical areas (Milly et al., 2002; Cudennec et al., 2007; Milly et al., 2008; Sheffield and Wood 2008). The above situation demands more efficient policies for water use, saving, harvesting, re-use and sanitation, along with improved strategies for prevention from, and adaption to, water related risks.

Figure 1. China's Huang He - or Yellow River, the muddiest river on Earth. Sediment deposition at the river delta caused dramatic change in river morphology and ecosystems in recent decades.

Sustainability of water uses has been a highly promoted principle in the recent past (Brundtland and World Commission on Environment and Development, 1987) and significant efforts have been made to embed it into several aspects of natural resources management and environmental preservation (Koutsoyiannis et al., 2009b). Given that strategies for sustainability generally require significant employment of economic resources, the current global economic crisis implies that substantial research and strategic efforts, within an interdisciplinary approach, are needed to ensure sustainable water uses for the future (Srinivasan et al., 2012). Thus, connections must be strengthened among engineering, hydrology, ecology and society, to provide stakeholders with a clear perspective of the priorities and advanced solutions for ensuring a sustainable development (Post and Moran, 2011).

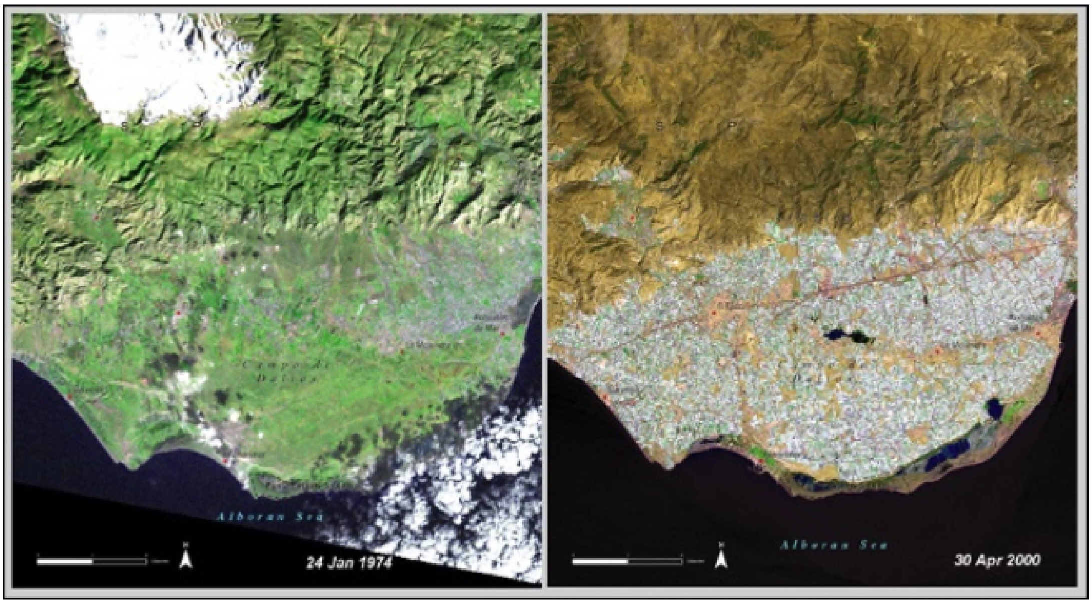

Figure 2. Africa's rapidly changing environmental landscape, from the disappearance of glaciers in Uganda's Ruwenzori Mountains to the loss of Cape Town's unique "fynbos" vegetation (source: UNEP)

Connecting hydrological processes with societal development is of paramount importance as people are becoming a dominant driver of change in hydrological, chemical, and energy cycles, and in landscape evolution (Matalas et al., 1982; Vitousek et al., 1997; Crutzen and Stoemer 2000; Rockstrom et al., 2009; Vörösmarty et al., 2010; Zalasiewicz et al., 2010. See also Figure 3). Human settlement patterns, economic production and demographics are impacting the availability and quality of freshwater resources, and the growing human populations alter the pathways and dynamics of hydrological processes to suit social needs. Rapid global population growth, along with significant changes in population distribution and increased appropriation of water supplies means that the intrinsic coupling of hydrological and human systems must be understood and represented from local to global scales to optimize water use efficiency and water allocations. Coupling spans both physical infrastructure and the many economic, policy and legal frameworks that govern water availability, use and pricing. Due to the social mechanisms, economic rules and institutional structures that are basic to human systems, it is the opinion of many researchers that human systems are far more diverse than natural systems (V. Srinivasan, IAHS Blog). Therefore, finding and studying the links and interactions between them becomes an extremely challenging issue.

Figure 3. Examples of interaction between environmental and human systems.

Changing conditions demand that societies adapt, which can be done in two ways: by mobilising more water or managing the water demand (Falknemark 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 resources management implies that a better comprehension is gained on 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 et al., 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 impacted by change whether human–induced or natural (Sivapalan et al., 2011; Wagener et al., 2010; Di Baldassarre et al., 2013b; Dessai and Hulme, 2007; Haasnoot et al., 2013; S. Schymanski, IAHS Blog).

Up to the present, 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 parameterised independently of possibly co–evolving processes. As a result, hydrology models were mostly intended to simulate and predict processes for catchments in pristine conditions, and the interaction with society was simulated by coupling them with independently developed models of societal behaviour. Within this framework, feedbacks between models have sometimes been schematised by introducing selected links among input and output variables as well as boundary conditions. Moreover, 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. This 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 like those of Mass et al. (1962) or Kneese (1964) in the early sixties – 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; Haasnot et al., 2013), with limited attention given to feedbacks and co–evolution.

With the current acceleration of the human impact 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, hydrology should not be separated from management (Nalbantis et al., 2011). The future of hydrology is closely related to improving our comprehension of changing behaviours of hydrological systems through the study of their two–way interaction with connected processes (Schaefli et al., 2011; Wagener et al., 2010; Baresel and Destouni, 2005; Baresel and Destouni, 2007). In particular, it is compelling to better study and represent the connection between water and humans, a concept studied in socio–hydrology (Sivapalan et al., 2012), which is one of the main drivers of change and is connected to sustainable water use and sustainable development (Figure 1. See also Liu et al., 2008; Savenije and Van der Zaag, 2008; Brookshire et al., 2012; Huang et al., 2013). Within this view, hydrological and connected models should not be developed independently, but through an improved comprehension of their complex connections.

To enhance the connection between hydrology and society we need to set up improved scientific interpretations of water cycle dynamics in time and space, as well a tight cooperation with economists and social scientists.

Figure 4. The Bund in Shanghai. A tremendous change occurred between 1990 (upper picture) and 2010 (lower picture).

Therefore, the consultation process concluded 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 a particular focus is placed on the interaction and feedbacks of 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) and the International Social Science Council (ISSC) and other major international organizations. Since water is a key element underpinning sustainability for society, seeking the connection and the synthesis of the research results of the two initiatives will represent a unique opportunity to foster interdisciplinarity.

Global research challenges require a community and coordinated effort to be effectively dealt with. The 90 years-long role and achievements of IAHS towards international cooperation, agenda setting and knowledge capitalization – all the more with the success of the recent 2003-2012 Prediction in Ungauged Basins (PUB) initiative of IAHS demonstrates that the community of hydrologists worldwide is looking forward to the identification of agreed research targets to increase coordination and mutual excitement. Thus, the identification of shared targets and research questions is a primary mission for IAHS, needing to be carried out with a forward-looking vision within our rapidly changing hydrological world.

Figure 5.Small cascade at Plitvice (Croatia). Ph.: A. Montanari

4. Perspectives on 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 dramatically changed. New methods and new research styles were introduced, as well as new research philosophies that changed the classical way hydrological problems are considered. The major changes were due to the increased availability of computing means, the increased availability of different kinds of data (and especially remotely sensed, global data), the increased visibility of research results after the widespread diffusion of web-based publishing, the increased number of publication venues and research groups working in hydrology all over the world. However, notwithstanding the continued efforts of IAHS to support networking and knowledge consolidation through decades (Rodda, 1981; Hubert, 2002; Cudennec and Hubert, 2008; Koutsoyiannis and Kundzewicz, 2008; IAHS, 2012) one notes that the connection among the above groups is weak, meaning that community building, aggregation, synthesis and dissemination remain a challenge.

The perspective on the next 10 years indicates that even more dramatic changes will occur in the research opportunities and practices. Computer capability will increase more and more, new data and computing means will facilitate the development of new theories which are required to progress for predicting hydrological change, therefore providing the potential to support new data analysis and verify new theories (Gupta et al., 2008; Bulygina and Gupta, 2009; Montanari and Koutsoyiannis, 2012; Kumar, 2011).

The near future will bring to our community impressive opportunities related to new monitoring and measurement techniques and, as such, research questions will emerge related to the use of the related information (Gupta et al., 2008; Kumar 2011; Gupta et al., 2012; 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? Is there any opportunity to reduce the current uncertainty of observations, which is often significant (McMillan et al., 2012)? Indeed, new observations will bring new insights, but we still poorly know how to integrate different types of information. It is therefore compelling to proactively devise new monitoring strategies (R. Hut, IAHS Blog; V. Smakhtin, IAHS Blog; G. Di Baldassarre, IAHS Blog) as well as new techniques for efficiently turning the raw data streams into useful information and ultimately new knowledge (S. Moges, IAHS Blog; G. Mahé, IAHS Blog; Gupta et al., 2008).

In fact, the massive expansion of availability of remotely sensed data will significantly change modelling approaches, in view of the possibility to observe the 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). 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). Many more examples of emerging monitoring technologies can be given, like 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 bringing interesting perspectives for traditional monitoring means. 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: modern technologies will allow reduction in the uncertainty associated with its direct measurements (Whitfield et al., 2012; Song et al., 2012).

It is worth noting that in some parts of the world investment in monitoring networks is actually decreasing: especially in the developing world, but also in developed countries that are affected by social, economic and political changes. Thus the scientific community needs to highlight clearly the importance of monitoring networks and developing long-term datasets to avoid the decline of hydrological information and also provide indications on how to prioritize measuring systems installation and maintenance, in light of resource constraints.

Innovative ideas are also being proposed to extract information from the data. There are many signatures in the observations that are still to be explored (Gupta et al., 2008; Wagener and Montanari, 2011; Toth, 2013; H. McMillan, IAHS Blog; P. Troch, IAHS Blog). The future of hydrology will certainly rely, even 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, Issue 5, 2006; see also Koutsoyannis et al., 2009 and Arheimer et al., 2011a).

Data-driven modelling techniques (See et al., 2007; Abrahart et al., 2012; E. Toth, IAHS Blog) may help 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 manner (including also soft and proxy data) and may therefore easily incorporate the measurements/sensing derived from new technologies.

Furthermore, hydrology will likely move from local analysis to multiple scales assessment of information. Virtual laboratories can be an extremely interesting opportunity to store large data-sets, set standards for retrieval and central storage of data (U. Ehret, IAHS Blog), as well as model calibration and validation (C. Perrin, IAHS Blog). They are an excellent opportunity to carry out comparative studies on multiple catchments (E. Boegh, IAHS Blog; P. Gentine, IAHS Blog; M. Sivapalan, IAHS Blog; Arheimer et al., 2011b) and data analysis in general (E. Toth, IAHS Blog).

In addition, the wide-spread 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 and the environment/water cycle.

Knowledge flows will be aided by emerging innovations in visualization technologies that can be used to communicate complex scientific information both within diverse research teams as well as to stakeholders and to the general public (Buytaert et al., 2012, Tidwell and Brink, 2008, White et al., 2008, Waser et al., 2010).

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

In summary, the next 10 years will bring impressive opportunities for research in hydrology, paving the way to new scientific approaches and modelling techniques. Therefore, devising a research agenda for the next decade requires a vision on 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.

5. Hydrology: a science projected in the future

IAHS research initiatives play a leading role in coordinating the efforts of the hydrological community. They provide input for education and inspiration 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 profiting at best from human and technical resources. This section presents a brief history of hydrology and elaborates considerations on its future, to conclude with the rationale for the need to focus on hydrological change and its implications for society.

Hydrology has a very 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 were observed by the Egyptians for the Nile 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 made by Perrault and Mariotte in the XVIIth century (Perrault, 1674), the modern quantified setting of hydrology appeared at around the middle of the XIXth century, when, for example, Mulvaney (1851) proposed the so-called "rational formula". Hydrology was substantially developed during the XXth century, when it became a fully independent science (IAHS, 2012). During the history of hydrology the 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 XXth century humans developed a multifaceted 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, a better comprehension was gained of the physics and stochastics of hydrological processes and the hydrological community increased in size world-wide. Over time the pivotal role of hydrological processes in dictating the relationship between humans and environment became increasingly clear. For example, land use change studies were typically a main driver for the development of hydrological sciences at its early stages (e.g. Crow et al., 1976).

It is without doubt that, with the current trend in societal and environmental development (Postel 2011; Sivakumar 2011; Famiglietti, 2012), the variability of hydrological conditions is increasing and endangers water uses and flood-prone settlements that are essential for societal security. Therefore, hydrology will become more and more important in the future and will unavoidably be more and more focusing 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 which impact the elements of hydrological cycle (Ren et al., 2012). The more society develops, over multiple time scales, the more it becomes effective on hydrological processes, by inducing perturbations that require an unnaturally quick adaptation (and related feedback) of water systems (Falkenmark and Lannerstadt, 2005). For this reason to gain an improved comprehension of change is an urgent necessity.

In summary, hydrologists will necessarily have to focus on the mutual relationship between water and society (see Figure 6, 7 and 8), given that hydrological processes are connected with human systems through multiple two–way interactions. Therefore, hydrological modelling should explicitly take into account these interactions 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 infrastructures, institutional means, economic conditions and social behaviours.

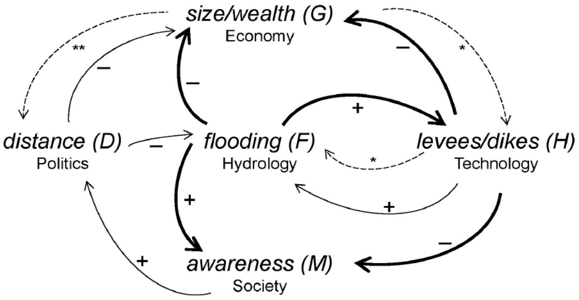

Figure 6 (from Di Baldassarre et al. (2013a)). Loop diagram showing how hydrological, economic, political, technological, and social processes are all interlinked and gradually (continuous thin arrows) co–evolve, while being abruptly (continuous thick arrows) altered by the sudden occurrence of flooding events. Dashed arrows indicate control mechanisms that are quantified by differential equations in Di Baldassarre et al. (2013a).

An example of the above integration is presented in Figure 6. 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 4 differential equations that are linked together and jointly solved.

6. The next IAHS Scientific Decade: Change in Hydrology and Society.

6.1 Why change is important for modern hydrology

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., 2009; Bloeschl 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 reasons 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 forcings to hydrological systems extremely diverse 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 e.g. 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; Koutsoyiannis, 2011). 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 recognised as the driver of significant perturbations on water systems (Brandimarte et al., 2011; Montanari, 2012). Unpredictability is strictly related to indeterminacy and uncertainty, and becomes more challenging as scale increases, 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 there has been increasing attention on human induced hydrological change, with several impact studies dedicated to scenario analysis. Although one cannot question that human activity is impacting hydrological systems, it is still unclear how the related feedbacks can be deciphered and modelled. The history of humans testifies that society evolved where water was available, often causing water degradation and threatening the survival of society itself. To better understand the mechanisms governing the above loop, with the related 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 7 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 (blue continuous line). After the human settlement a perturbation is induced whose feedback generally provokes a decrease of the resource that is independent of its possible exploitation (red line). For instance, artificial reservoirs increase evaporation and therefore induce a corresponding diminution of the river flow volume. Moreover they often imply a change in groundwater recharge and therefore in downstream groundwater bodies. Part of this altered (after feedback) amount of natural resources is then exploited (and degraded) by society therefore further reducing their availability (blue line after human settlement). Such feedbacks and exploitation have dramatically increased in recent times (Steffen et al., 2011) and a first challenging question is related to their interaction with natural variability.

While exploitation is relatively easy to estimate, the feedbacks - like those triggered by the above mentioned 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 is needed to be able to make predictions to support the management of natural resources.

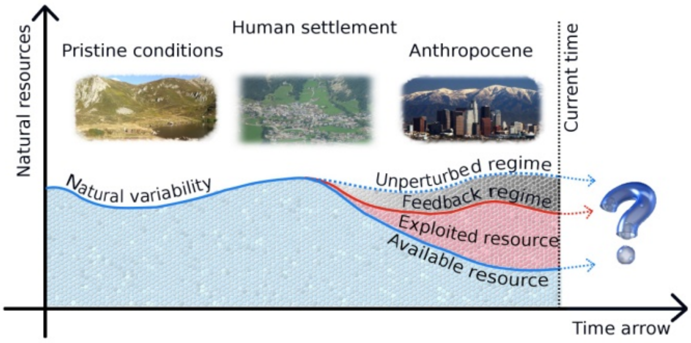

Figure 7. Sketch of the progress of human induced hydrological change over time.

New coordinated research is needed to decipher and predict the impact of society on hydrological systems in the long term, by studying how society and hydrological processes have co-evolved in history and keep co-evolving (Sivapalan et al., 2011; Wagener et al., 2010; S. Schymanski, IAHS Blog).

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

6.2 How to assess and model hydrological change

Human induced changes are superimposed to natural changes, for the natural inclination of human beings to modify the environment to improve life conditions. The impact of human activity is particularly relevant in urbanized areas and may have a significant effect on water resources availability and water related risks (Di Baldassarre et al., 2010). The superimposition of several changes occurring at different spatial and temporal scales makes the interpretation and modelling of change extremely complicated, therefore justifying the interest for the hydrological community in change-related problems.

Indeed, new paradigms, approaches and taxonomies (Thompson et al., 2013) are needed to take change into account in hydrological analyses and assessments, in view of the links between hydrology, environment and society (see Figure 8; see also Schaefli et al., 2011). New schemes are needed where links and feedbacks among the above components are explicitly considered (see Figure 9).

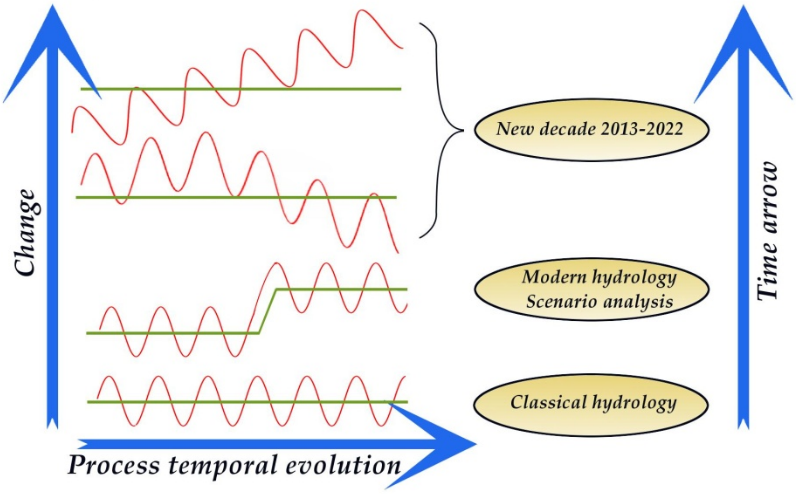

Figure 8. Progress of change treatment in hydrological sciences, from steady state in classical hydrological, sequence of steady-states in modern hydrology and long term changes and unsteady state in the future.

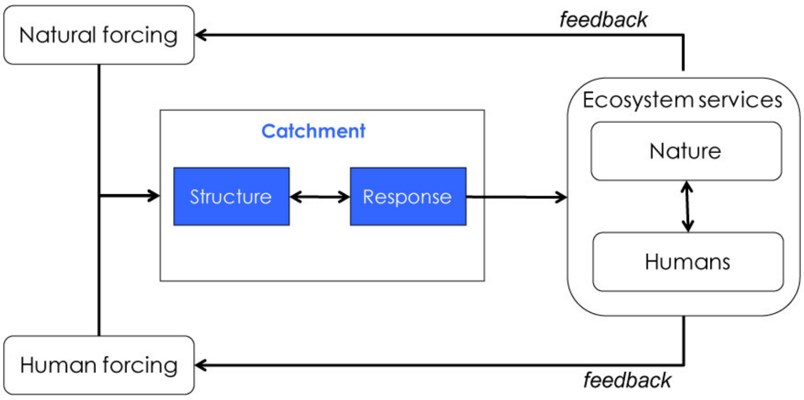

Figure 9. Links and feedbacks among catchment, ecosystems and society (Credit: Bettina Schaefli)

The literature proposed several approaches for interpreting the dynamics of changing systems. Some of them date back several decades and are related to stochastic modelling of stationary and non-stationary systems. Indeed, a first relevant question is related to the identification of the modelling approach.

6.2.1 Change detection and attribution: Newtonian and Darwinian approach

How can contemporary hydrologic science respond to the challenges posed by environmental change? It has long been recognized that “business as usual” is unlikely to be sufficient (Dooge 1986; Dooge 1988; Gupta et al., 2000; Torgersen 2006; Hooper 2009). A re-examination of the fundamental models used in hydrology is required. Contrasting approaches have characterized the study of environmental change, reflecting the intellectual traditions of different disciplines. Several authors (see, for instance, Harte (2002)) suggested that contemporary challenges in the earth sciences may require a synthesis between the “Newtonian” and “Darwinian” approach, particularly when dealing with biotic and human interactions with the physical world (Sivapalan et al., 2013).

The Newtonian approach, exemplified in hydrology by detailed process-based models, values understanding built up from universal laws that govern the individual parts of the system. The objective is to mechanistically characterize how water, energy and mass fluxes and transformation occur in each element of the landscape – be it a channel reach, a volume of porous media, a plant stoma or canopy, or the atmospheric boundary layer. This understanding is not tied to a particular landscape: the laws being sought are universal. However, their solution depends strongly on the boundary and initial conditions, which must be characterized for a particular landscape. In non-static, interconnected landscapes, coupled to human societies, devising such universal laws and being able to use them for prediction is a considerable challenge.

The Darwinian approach values a holistic understanding of a particular landscape system. It is exemplified by much of ecology. This approach embraces the history of particular places, including those features that are relics of historical transformative events (such as fire, human activities, ecological invasions) as central to understanding its present and future. Laws in the Darwinian approach describe patterns of variation and commonality across sites selected to characterize critical gradients. A Darwinian approach allows human connections to the water cycle to be studied by linking patterns of social behaviour to the different properties of the systems in which those behaviours arise, and by exploring and understanding their historical trajectories of change (Sivapalan et al., 2011; Blöschl et al. 2013, ch. 12; C. Harman, IAHS Blog).

A synthesis between the Newtonian and Darwinian approaches in hydrology offers the possibility for combining our predictive understanding of the mechanisms of change with our explanatory understanding of the patterns that emerge when these mechanisms interact in real landscapes. Such a synthesis could provide a breakthrough for addressing the challenges of making predictions under changing conditions. While it may not be clear how that synthesis will look until it is achieved, we can predict some features that are likely to be important elements.

Independently of the modelling approach, an essentially prerequisite for taking change into account is to decipher it, namely, to assess and attribute change. Detection of change must be carried out by assessing changes either in the variables (in the deterministic approach) or in the statistics of the variables (in the stochastic approach). The assessment is complicated by the possible presence of long term persistence (LTP) in geophysical processes, also known as “Hurst Effect”, which means that the process itself is prone to long term cycles, therefore making the attribution of change problematic.

There is an extensive literature in change assessment and attribution for hydrological variables, which is frequently referring to local variables. There is still much unexplored information that may allow us to gain deeper insights into the processes and their dynamics. In particular, the analysis of spatially distributed variables, and the analysis of the connections between coevolving processes, is an interesting way forward to improve change attribution and detection.

6.2.2 Modelling change: deterministic and stochastic approaches

Hydrological variables can be modelled either as deterministic or random. Process-based models are almost always formulated in deterministic form, by setting up a set of mathematical equations. In a deterministic model the outcomes are precisely determined through known relationships among states and events, without any room for random variation. A given input (including initial and boundary conditions) will always produce the same output and therefore uncertainty is not taken into account in a formal manner. Uncertainty assessment, when needed, is often carried out indirectly, e.g., by post processing the results (Montanari and Koutsoyiannis, 2012).

In a stochastic model the outcome is a collection of random variables; this is often used to represent the evolution of some random value, or system, over time. Instead of describing a process which can only evolve in one way (as in the case, for example, of solutions of an ordinary differential equation), in a stochastic or random process there is some indeterminacy: even if the initial condition (or starting point) is known, there are several (often infinitely many) directions in which the process may evolve (see http://en.wikipedia.org/wiki/Stochastic_process).

The selection between deterministic and stochastic approaches should be dictated by the researcher's choice to formally or not take into account random variations in the system. These latter maybe induced by epistemic uncertainty (incapability to fully represent the involved processes in a deterministic framework) as well as by inherent indeterminacy.

6.2.3 Modelling change: co-evolution of systems

Mechanistic predictions that account for change must link the propagation of variations in drivers (human demands/climate) or structure (land use, hydrological flow paths and storages), to variations in the dynamics of a watershed. Variables that are often treated as fixed, such as soil structure, landscape topography, ecosystems and land use, are likely to respond to externally imposed changes (Sivapalan et al., 2013; Schaefli et al., 2011). Soils, geomorphology and ecology are all coupled to water cycle dynamics (C. Harman, IAHS Blog). Water is a major determinant of ecological organization, particularly in dry parts of the world. It shapes the physical and biogeochemical organization of soils by dissolving or suspending and transporting minerals and nutrients. Water does much of the geomorphic work that shapes the land surface. In human-dominated systems, the dynamics of the water cycle drive the development of engineering infrastructure and governance mechanisms. Predictions about water availability across space and time must therefore consider the connections between the water cycle and climatic, ecological, social and earth surface change (Figure 10).

This is challenging for several reasons. First, it pushes hydrologists to treat watersheds as complex inter-connected systems, opening up a new set of theoretical and practical difficulties. Second, the timescales associated with hydrologic, ecologic and geomorphologic changes may be very different: although major changes in all three are often associated with fast events, the length of time between these events tends to be shortest for hydrology (inter-storm timescales), than ecology (decadal or longer) and longer still for geomorphology (see Gaal et al., 2012, fig. 12). Understanding how fast processes influence the slower responses of life and landscapes is difficult in terms of both observations and theory. Finally, understanding the implications of interconnectedness on long timescales and large spatial scales exacerbates the already severe up-scaling challenges facing hydrology (Blöschl and Sivapalan 1995; McDonnell et al., 2007). Given these challenges, the emergence of structure and organization in the landscape such as river network structure, hydraulic geometry, soil catena, and vegetation patterns offer an alternative way to investigate the interconnectedness of human, physical, biogeochemical, and ecological processes that interact and feedback on each other to cause organization to emerge across multiple spatial and temporal scales.

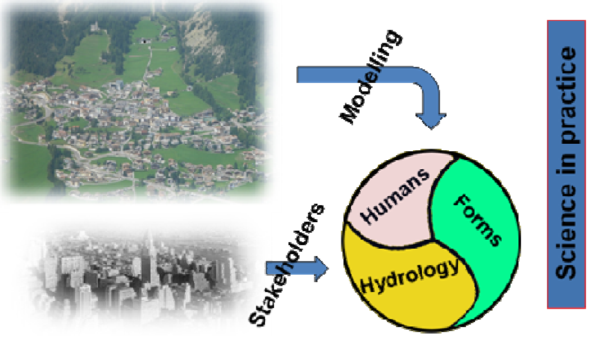

Figure 10. Co-evolution of hydrological systems with society and catchment forms.

6.2.4 Modelling change: entropy

It was mentioned above that the second law of thermodynamics, stating that entropy tends to increase, is the explanation of changes occurring in natural systems. In fact, the tendency of entropy to naturally increase explains why natural processes evolve, although conservation laws alone may allow stagnancy. Therefore, the concept of entropy plays a key role in change modelling, but its use to model hydrological processes requires a paradigm shift

6.3 The subject of the new decade: Hydrological change

The above considerations show that several options are available for change assessment, attribution and modelling. Yet, the application of the above approaches for reaching a better interpretation of natural-human systems and the solution of engineering problems is still a challenging task. Innovative research findings are needed to devise agreed protocols of research to improve our prediction capabilities and therefore our ability to tackle emerging water resources management and socio-hydrological problems. A coordinated community effort is needed to address the above challenges, which require a consistent definition of the problem, relevant data acquisitions, new theories and the identification of self-organizing principles driving co-evolution for developing a modelling framework to provide an interpretation of the processes with uncertainty assessment.

6.4 Seeking connection with society

The new decade of IAHS aims at reinforcing the role of hydrology as the key evolving interface between environment and society. To better connect environmental change with societal change one needs to include the water cycle in the modelling system as an evolving component that is directly linked, with feedbacks, to humans and the earth system. To stress this fundamental role of hydrology, an improved connection with society is needed, through an interdisciplinary approach involving social scientists, economists, ecologists, decision makers and users.

To reach the above goal, it is essential to estimate and efficiently communicate uncertainty, which plays a relevant role in social sciences (G. Baroni, IAHS Blog; L. Brandimarte, IAHS Blog; C. Stamm, IAHS Blog; H. Gupta, IAHS Blog). Uncertainty is not just a research theme on its own: it is an essential link with society.

IAHS can play a very influential role to seek connection with human systems through its commissions, National Hydrological Societies and through dissemination (Cudennec and Hubert, 2008; V. Smakhtin, IAHS Blog; A. Viglione, IAHS Blog).

7. The next IAHS Scientific Decade: the Science Plan

7.1 Title and acronym

PANTA RHEI – Change in hydrology and society

“They must often change, who are constant in happiness and wisdom” – Confucius (551 a.c. – 479 a.c.)

“Nothing is permanent but change” – Eraclitus (535 a.c. – 475 a.c.)

“If anybody wants to keep creating they have to be about change” – Miles Davis (1926 – 1991)

The topic of “Change in Hydrology and Society” for the Scientific Decade 2013-2022, identified by the consultation process stimulated 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 sentence 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.

Panta Rhei aims to bring the hydrologic community together under a common umbrella to undertake pioneering research for 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, and hopefully it will eventually influence the way in which hydrology is taught (hydrological education). Panta Rhei is an inter-disciplinary initiative: it will involve collaborations and interactions 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).

The logo of Panta Rhei is shown in Figure 11. The Science Plan, that was shaped and refined with an unprecedented community concerted effort and synthesis (see introduction), is available for download at the IAHS web site (www.iahs.info).

Figure 11. 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 the society.

7.2 Summary

The Scientific Decade 2013-2023 of the International Association of Hydrological Sciences will focus on the analysis, interpretation and modeling of changes in hydrological systems, and their links with natural variability, human impact and human needs, to address emerging instances from society in relation to water. The scientific objective 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 concept implies a focus on hydrology as a changing part of the coupled societal and environmental system, whose dynamics are essential to determine the impact of environmental change. Changes are defined as long term or irreversible modifications along the time arrow of the system's configuration, including boundary conditions, input data and internal dynamics. Past research activity dedicated ample focus on the temporal variability of hydrological processes, including changes induced by seasonality, land use changes and assigned scenarios of climate change. In fact, the impact of long term or irreversible changes has been mainly studied in the past through scenario analysis, which leaves many questions open about its representativeness and uncertainty. The Scientific Decade 2013-2022 will focus on ameliorating the comprehension of unsteady behaviours of the Earth system and ultimately the water cycle, by devising innovative theoretical blueprints for processes representation including change and by profiting from advanced monitoring and data analysis techniques. The objective is to improve change quantification, attribution and modeling, with the ultimate goal to enhance predictability and technical applications. Interdisciplinarity will be sought by bridging with socio-economic sciences and geosciences in general.

7.3 Keywords

Understanding, Modelling, Change, Society, Hydrological Prediction, Uncertainty, Indeterminacy, Risk, Vulnerability, Coupled human-water systems, Freshwater security, Water sustainability, Co-evolution; Environment, Observations, Socio-hydrology.

7.4 Concepts of Panta Rhei

The main concepts for the scientific activity being developed in Panta Rhei can be summarised in the following statements.

- The interaction between hydrology and society is changing, therefore implying 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 the 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 recognised 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 (Figures 9, 10 and 12).
- 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 the environment itself.
- Change is resulting from the superimposition of natural variability and human induced effects. 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, therefore emphasising 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 ongoing success of hydrological science as well as 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 an immense potential in terms of research contribution and community building.

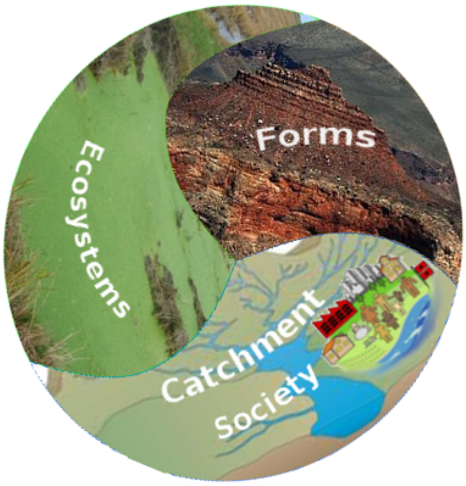

Figure 12. Interactions among ecosystems, forms, hydrology and society.

7.5 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. The 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. During the IAHS Scientific Decade 2013-2022, the research targets below will be pursued, by means of the Science Questions outlined in the Section 7.6.

Target 1 –Understanding

This 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. Special attention is to be devoted to complex geographic systems like 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

This is closely related to and the utility of understanding, and it is the essence of hydrologic engineering and hydrological applications, embracing flood risk mitigation and water resources management. Target 2 includes estimation of design variables under change and uncertainty assessment that is a crucial step to support risk evaluation. The interdisciplinary focus of Panta Rhei will contribute to an improved understanding of the interaction among 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 humans in the study of hydrological systems and therefore aims at an iterative exchange between science, technology and society. Science in practice is science for people and therefore is relevant science (both fundamental and applied) and relevant water technology. It includes policy-making and implementation. The fact that hydrology is relevant to society implies the identification of societal needs for water – for the various water uses – as well as the threats that water poses in terms of floods, land degradation and droughts. Here we need a shift in paradigms of modern water management based on equities between demand and supply driven activities.

Panta Rhei recognizes the feedback between each of the three targets: improved understanding may potentially lead to more accurate predictions, which helps sustainable management. However, management itself can contribute to the cycle of understanding. Figure 13 summarises the interactions among the targets of Panta Rhei.

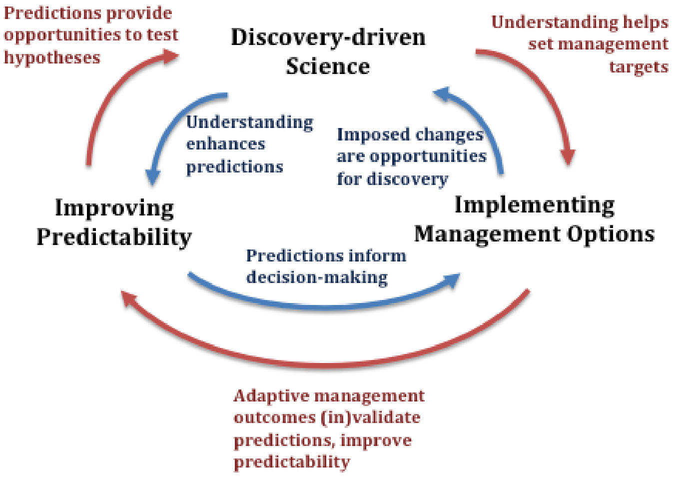

Figure 13. Hydrology as a discipline spanning natural science, social science, engineering and management goals; these goals can interact synergistically. Credit: Sally Thompson.

7.6 Science questions

The study of change in hydrological systems and society implies fundamental science questions that in Panta Rhei have been deliberately kept few and concise. They have been formulated after a specific consultation of the community through the IAHS blog and milestones meetings.

Science question 1 (SQ1, Target 1)

"What are the key gaps in our understanding of hydrologic change?"

Science question 2 (SQ2, Cross-cutting targets)

"How do changes in hydrological systems interact with and feedback on natural and social systems driven by hydrological processes?"

Science question 3 (SQ3, Cross-cutting targets)

"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, Target 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 targets)

"How can we advance our monitoring and data analysis capabilities to predict and manage hydrologic 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 hydrologic 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.*

7.7 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 Figure 14). 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 involvement and cohesion of the hydrological community and the exchange of experiences with sister disciplines, and in particular the social sciences. The activity will be driven by the science questions and addressed to 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 allow attainment of a better comprehension of hydrological systems in their entirety. To gain an interpretation of hydrological change and to understand the implications with connected sciences, we need an improved comprehension of the internal dynamics of hydrological processes and their connections with 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 and feedbacks with 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 naturally 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.
- Entropy modelling and evolution of natural systems.

A special focus is given by SQ2 to assess 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.
- 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.

SQ 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.
- Development of advanced prediction methods in the presence of indeterminacy.

SQ5 focuses attention on recent technological developments, which offer opportunities for improved hydrological monitoring. They will heavily 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.
- Linking new observations and techniques with historical data sets.

SQ6 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 ongoing 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 for human–induced changes of the hydrological conditions.
- Transboundary water resources management, and water conflicts.
- Impact of large-scale water structures and large-scale water transfer.

The above research topics open several exciting avenues for research, by 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 therefore producing a non–stationary output. Another example could be the incorporation of human dynamics when modelling groundwater–surface water interaction, therefore accounting for artificial water storage, water withdrawal and so forth.

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 be kept connected with the main international research organisations to ensure a full connection with the global hydrological community.

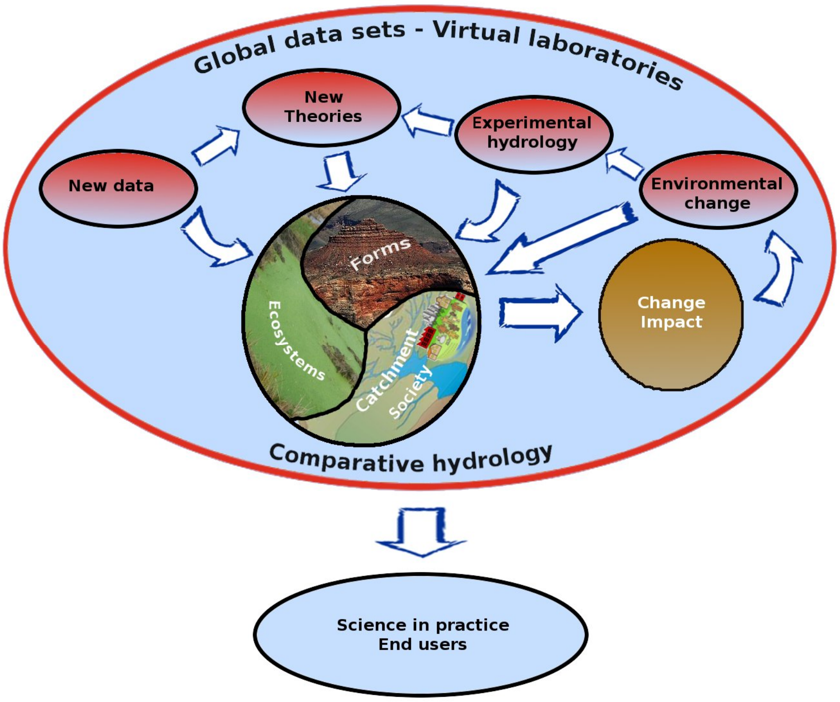

Figure 14. Enabling research in Panta Rhei

7.8 Implications in hydrology education

The ideas and results of Panta Rhei can be readily implemented in education. There are already significant examples where the concept of hydrological change is taught in degree and doctoral programs (Blöschl et al., 2012; Seibert et al., 2012; see also the special issue of Hydrology and Earth System Sciences “Hydrology education in a changing world”, J. Seibert, S. Uhlenbrook, and T. Wagener eds., vol. 16, 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.

7.9 Implications in operational hydrology and management

Knowledge transfer is an essential issue 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 descends from addressing real world water issues. Panta Rhei will continue this tradition by reinforcing the connections with governmental and non-governmental organisations, water managers and local administrations. Moreover, Panta Rhei will set the basis for seeking an improved connection with national and international funding agencies.

7.10 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 separated fields, each one editing its journals, organising its workshops and symposia and individually recognising the value of its research. Such organisation does not automatically promote a better interaction among sister disciplines, and 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 with a different perspective with respect to hydrology. In particular, the following actions will be promoted:

- identification of joint research themes;
- joint workshops, symposia and editorial initiatives;

- activation of initiatives within the hydrological community to promote and recognise 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 in the whole course of the SD.

7.11 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 (Hrachowitz et al., 2013; UN–Water, 2012).

Panta Rhei aims to act as a catalyst by pursuing an innovative approach, whose distinctive behaviours are: (a) to include human activity as a more integral dimension of hydrological science, therefore implying the opportunity to shift the focus from pristine catchments to human impacted environments; (b) to derive general findings, therefore supporting the development of results of general validity from the numerous case studies that the community is developing.

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 the above 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 it is traditionally done, may be more practical but in other cases representing the two-way feedbacks in a dynamic way will be essential. Improving the comprehension and representation of the above links will allow generalisations 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.

8. The next IAHS Scientific Decade: Structural Organisation

The structural organisation to manage the coordination of the next Scientific Decade will be discussed by the IAHS Bureau. The following key issues have been decided:

- The Decade will be divided into five Biennia (as with PUB); a theme will be defined for each biennium, and each biennium will be coordinated by a chair.
- The three targets are set and will be tackled simultaneously.
- Leaders for each target will be appointed and their work will be coordinated through the chair.
- Research themes will be defined, which will refer to the Science Questions and Targets. Themes can be defined before and after the launch of the new decade. An implementation plan will be presented in Gothenburg presenting WG and guidelines for establishing WGs. Connection with social sciences and society will be an essential requirement.
- The activity will be carried out by setting Working Groups (WG), whose activity will refer to research themes. WGs can be defined before and after the launch of the new decade.
- IAHS Commissions and National Hydrologic Associations will be directly involved in the activity. Involvement of end users will be considered with particular attention.
- The final reporting structure and the development of Working Groups will be decided by the Bureau prior to and during the Gothenburg Assembly.

In detail The Science Initiative of IAHS for the decade 2013-2022 will be structured accordingly to the PUB organizational model that proved to be successful. Accordingly, the research will be carried out through a global network of Working Groups (WGs) comprising interested researchers in any area of Panta Rhei, cutting across traditional thematic areas. WGs will be the main engines of the research activities. WGs shall define their own objectives but will be required to have an emphasis on enabling comparability of different approaches towards well-defined common goals, including reduction of predictive uncertainty. The emphasis on comparability of activities within and between WGs is aimed at value adding to individual research efforts, and helping to harmonise and reach consensus, in approaches to making hydrologic predictions.

The coordination of the research activities will be managed by a Scientific Steering Group, which will be coordinated by a Chair that will be rotated every 2 years.

9. Conclusions

The new scientific decade of IAHS 2013-2022 entitled Panta Rhei focuses on Change in Hydrology and Society. Panta Rhei will be the leading motif of IAHS in the next 10 years: by including environmental feedbacks and humans as an essential part of hydrological systems. Panta Rhei, which represents a major paradigm shift in hydrological sciences, is a challenging initiative which requires considerable reorganization of the way hydrology is studied, taught and applied. It will bring together scientists of different communities and represents a genuine chance to bring people together globally to address problems that can only be solved through community efforts at all levels.

Panta Rhei will be a scientific grassroots 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 ameliorated 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 awareness in 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 environment and human needs for water and understanding hydrological change is the key to planning sustainable water exploitation and therefore water supply, water sanitation, water for food, energy production and 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.

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