INTERNATIONAL ASSOCIATION OF HYDROLOGICAL SCIENCES
ASSOCIATION INTERNATIONALE DES SCIENCES HYDROLOGIQUES

International Association of Hydrological Sciences
Association internationale des sciences hydrologiques

SCIENCE PLAN FOR THE DECADE 2013-2022

Panta Rhei

Change in Hydrology and Society

First version (draft) prepared by:

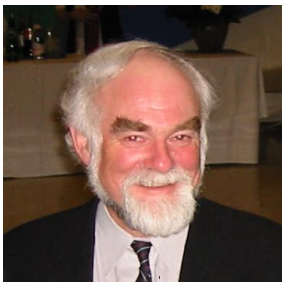
IAHS Task Force on the Scientific Decade 2013-2022
(Alberto Montanari – Chair)

Revised by (at Nov 22nd, 2012):
Gordon Young – IAHS President
Christophe Cudennec – IAHS General Secretary
Demetris Koutsoyiannis (Deputy Editor of Hydrological Sciences Journal)
Murugesu Sivapalan (University of Illinois)

November 22, 2012

Table of contents

1. Foreword



Foreword by IAHS President Prof. Gordon Young to be added later

2. Background

The International Association of Hydrological Sciences (IAHS) was established in 1922 and has over 5400 individual members around the world. As a science association, IAHS is engaged in various activities 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 will be published by Cambridge University Press in 2013 along with a companion book on "Putting PUB into Practice".

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 is still 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.

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 to 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 success of PUB in terms of community building calls for a collective and unified effort in the new decade. **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 water resources management, water quality and an accurate investigation of the links and feedbacks between hydrology and society (Sivapalan et al., 2011). 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). The general and rapid increase of the socio-economical 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, 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 ongoing 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 for 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 hydrology, geosciences in general and society.

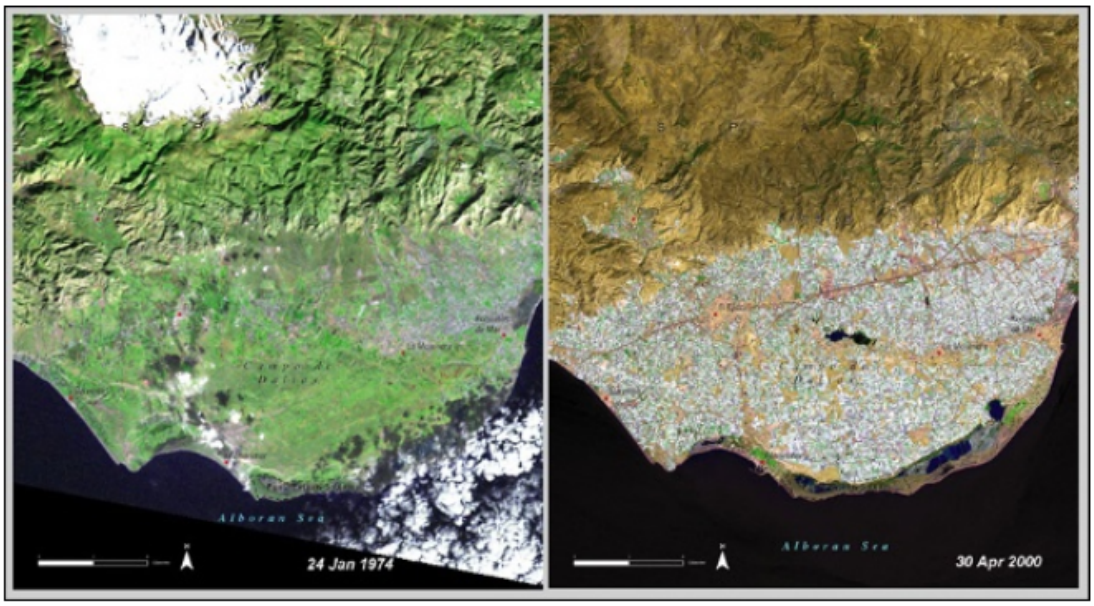


Figure 2. Africa's rapidly changing environmental landscape, from the disappearance of glaciers in Uganda's Ruwenzori Mountains to the loss of Cape Town's unique "fynbos" vegetation (source: UNEP)

Connection with society is of paramount importance as people are becoming a dominant driver of change in water, nutrient, and energy cycles, and in landscape evolution (Vitousek et al. 1997; Crutzen and Stoemer 2000; Rockstrom et al. 2009; Vorosmarty et al. 2010; Zalasiewicz et al. 2010). Human settlement patterns, economic production and demographics are related to the availability of freshwater resources so that growing human populations alter natural water systems to suit social needs. Rapid global population growth, along with significant changes in population distribution and increased appropriation of water supplies means that hydrologic and human systems are now intrinsically coupled from local to global scales. Coupling spans both physical infrastructure and the many economic, policy

and legal frameworks that govern water availability, use and pricing. It is the opinion of many researchers that human systems are far more diverse than natural systems (V. Srinivasan, IAHS Blog). Therefore, once socioeconomic and institutional diversity is coupled with hydrologic diversity, finding patterns becomes an extremely challenging issue.

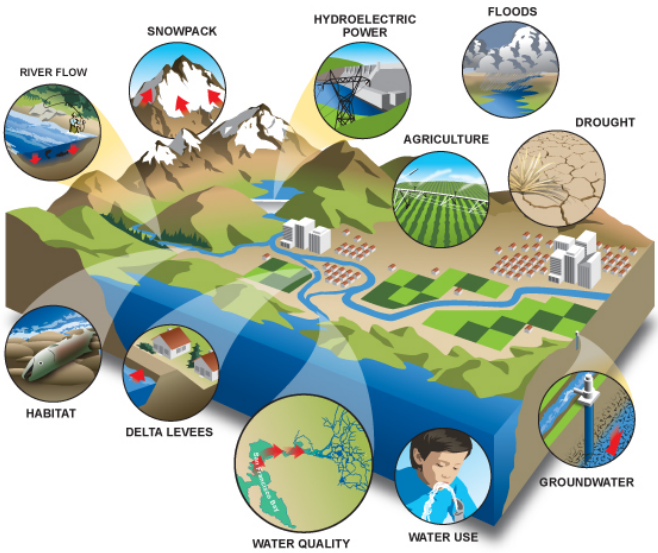


Figure 3. Links between hydrology and society (credit: California Department of Water Resources, http://www.water.ca.gov/climatechange/factsheet.cfm

The solution of the above problems requires the setting up of more informed water resources management policies, which in turn require improved scientific interpretations of water cycle dynamics and connections with geosciences in general, as well as economics and social sciences. In particular, a better comprehension is needed on the reaction of hydrological systems and processes to changing conditions and forcings, in relation to societal development. Classical hydrological analyses have been founded on the assumption of static systems, that in many cases produced satisfactory predictions in the short and, sometimes, long term. However, hydrologists have always had the clear perception that hydrological systems are changing, at the very least because the earth system itself is continuously changing. Human induced modifications are superimposed on natural changes, for the natural inclination of human beings to modify the environment to improve life conditions. Thus, it has been always clear that the static assumption, although useful, is not valid in the long term. Today, the rapid increase of societal development and human impact calls for a better interpretation of the above changes and improved

predictions, which are made possible by progressing geosciences, monitoring capabilities and computing means. Thus, hydrological change is unanimously recognized to be a topical issue for hydrologists.

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

However, it is still unclear how change can be modelled besides the traditional "top down" scenario approach. This latter is carried out by identifying and calibrating hydrological models in current conditions and then running them with perturbed parameters or input data according to assumptions on changes in forcings and/or dynamics. The top down approach has been used in several studies already. On the one hand, it provided useful results. On the other hand, it has proved to be affected by significant limitations due to limited credibility of current models under changing conditions, uncertainty in future trajectories and model parameters. The results so far obtained call for improved approaches to better understand the interaction between hydrological systems and changing socio-economic and environmental forcing, besides what perturbations in input data and parameters suggest (S. Thompson, IAHS Blog).

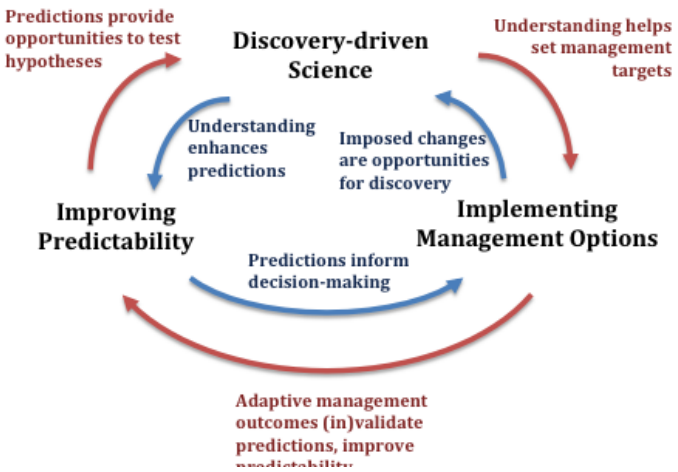


Figure 5. Hydrology as a discipline spanning natural science, social science, engineering and management goals; these goals can interact synergistically. Credit: Sally Thompson.

The above considerations clearly identify the way forward for hydrology in the near future, its complexity and therefore attractiveness. The availability of modern monitoring systems and computing facilities, as well as recent research results, open new and exciting doors to tackle the above scientific challenges in the next 10 years. Spatially extended data sets and open data make systematic hypothesis testing an invaluable opportunity for future research, allowing to trade space for time and to inspect the structure of water systems and their co-evolution with environment (C. Harman, IAHS Blog).

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 question is a primary mission for IAHS, which needs to be carried out with a forward-looking vision within our rapidly changing hydrological world.

Figure 6.Small cascade at Plitvice (Croatia). Ph.: A. Montanari

4. Perspectives on the research opportunities in hydrology for the next 10 years

Looking back 10 years in the world of hydrological sciences, one notes that research is dramatically changed. New methods and new research styles were introduced, as well as new research philosophies which changed the classical way hydrological problems are considered. The major changes were due to the increased availability of computing means, the increased visibility of research results after the widespread diffusion of web-based publishing, the increased number of publication venues and the increased number of research groups working in hydrology all over the world. Still, one notes that the connection among research groups working in hydrology in different continents is weak, meaning that community building and aggregation still remains an exciting challenge.

The perspective on the next 10 years indicates that even more dramatic changes will occur in the research opportunities and practices. Computer means will progressively increase therefore making numerical integration and simulation in general a standard tool. Moreover, substantial progresses are expected for monitoring techniques. The massive availability of remotely sensed data will significantly change modelling approaches, in view of the possibility to observe most of the constituent variables in the land surface water balance (e.g., precipitation, evapotranspiration, snow and ice, soil moisture, and terrestrial water storage variations).Indeed, remote sensing is a viable source of observations of land surface hydrologic fluxes and state variables, particularly in regions where in situ networks are sparse. 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.

New monitoring techniques are also expected to become current practice, like the use of digital cameras and cell phone signals to retrieve rainfall intensity. In fact, over the last decade, wireless communication networks have grown to cover huge areas by dense meshes and, being impaired by precipitation, may therefore be considered as large-scale, high resolution atmospheric observation networks with practically no additional maintenance cost. Reliability of estimates heavily depends on the density, homogeneity, and operation conditions of the mobile phone networks, which are expected to improve in the next few years. Many more examples of emerging monitoring technologies can be given, like distributed temperature sensors, new tracer and so forth.

For sure, the future of hydrology will rely, even more than in the past, on exploiting the information from data. There is the need to move from local analysis to spatially distributed assessment of information. Data sharing will be a key means to reach this target, as well as open source research. Virtual laboratories, where data, metadata

and protocols can be shared among several research group, will be the tools to assess changes of water systems in space and time.

In fact, 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 the rule and a necessity for the future, therefore ensuring exchange of ideas and opportunities (including funding). The time of individually produced research, which produced relevant results in classical and modern hydrology, is close to its end. Cooperation will drive significant changes in the research practice and will definitely be an important opportunity for pursuing interdisciplinarity, which is today recognized as an essential prerequisite to allow the synthesis of the massive research activity that is being developed.

The near future will bring to our community impressive opportunities related to new monitoring and measurement techniques and, as such, research question will emerge related to the use of the related information (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? Indeed, new observations will bring new insights. It is 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 extracting information from several data sources (S. Moges, IAHS Blog; G. Mahé, IAHS Blog). Virtual laboratories can be an extremely interesting opportunity to store large data-set, set standards for retrieval and central storage of data (U. Ehret, IAHS Blog), as well as model calibration and validation (C. Perrin, IAHS Blog). Also, virtual laboratories are an excellent opportunity to carry out comparative studies on multiple catchments (E. Boegh, IAHS Blog; P. Gentine, IAHS Blog; M. Sivapalan, IAHS Blog) and data analysis in general (E. Toth, IAHS Blog).

Last but not least, attention should be devoted to innovative ideas to extract information for the existing data. There are many signatures in the data which are still to be explored (H. McMillan, IAHS Blog; P. Troch, IAHS Blog).

In summary, the next 10 years will bring impressive opportunities for research in hydrology, opening 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, to effectively drive the community effort that is needed to address the research challenges related to the analysis and modelling of changing hydrological systems.

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

5.1 Why change is important for modern hydrology

A better comprehension of water management problems that confront society today requires that phenomena connected with the water cycle, for instance freshwater availability, circulation, distribution, and quality, be simulated and predicted in systems that are heavily impacted by change whether human-induced or natural (Sivapalan et al., 2011; Wagener et al., 2010; S. Schymanski, IAHS Blog). Actually, hydrological analysis have been often founded on the assumption of static systems, which is a practical solution to solve water resources management and engineering problems in the short and, in some cases, long term. However, with the current acceleration of the human impact it is becoming increasingly clear that accounting for change is necessary to reach a better interpretation of coupled human-natural systems. In fact, hydrologists have always had the perception clear that hydrological systems are changing, at the very least because the earth system is continuously changing in its own. Solar activity, climate and consequently the water cycle are continuously undergoing significant changes that in some cases are perceived even during one's life span.

Change in natural systems is explained by the second law of thermodynamics, which states that the entropy of an isolated system (and hence of the whole universe) always increases or remains constant. Among the most familiar evidences of increasing entropy is that in heat transfer situations, heat energy is transferred from higher temperature to lower temperature components according to an irreversible process.

The tendency of entropy not to decrease implies that some processes (permitted by conservation laws) occur spontaneously while their time reversals (also permitted by conservation laws) do not. This fact has several important consequences in science: it implies, first, that perpetual motion is not possible; second, that the arrow of entropy has the same direction as the arrow of time; third, that system states that have higher entropy are more likely to occur and thus if a system happens to have low entropy, it is likely to change so that its final entropy gets increased. The latter implication explains why change happens in nature. Increases in entropy correspond to irreversible changes in a system, because some energy is expended as waste heat, limiting the amount of work a system can do (Atkins, 2007; Koutsoyiannis, 2011).

5.2 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 the 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 (S. Thompson, to be published in Sivapalan 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 also Schaefli et al., 2011). New schemes are needed where links and feedbacks among the above components are explicitly considered (see Figure 7).

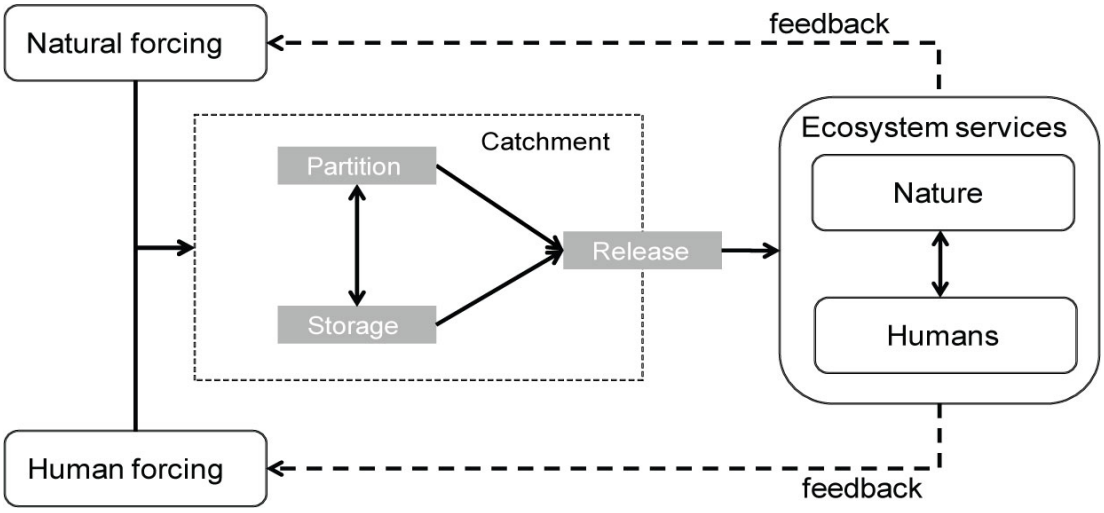


Figure 7. Links and feedbacks among catchment, ecosystems and society (Credit: Bettina Schaefli)

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.

5.2.1 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; 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:

5.2.2 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.

5.2.3 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.

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), then ecology (decadal or longer) and longer still for geomorphology. 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.

5.2.4 Modelling change: entropy

It was mentioned above that the second law of thermodynamics, stating that the entropy tends to increase, is the explanation of changes occurring in natural systems. In fact, the tendency of the 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

5.2.5 Change detection and attribution

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.

5.3 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, the identification of self-organizing principles driving co-evolution and the setting up of a modelling framework to provide an interpretation of the processes with uncertainty assessment.

5.4 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 which 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, 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, the National Hydrological Society and through dissemination (Cudennec and Hubert, 2008; V. Smakhtin, IAHS Blog; A. Viglione, IAHS Blog).

6. The next IAHS Scientific Decade: the Science Plan

6.1 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)

6.2 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 to 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. Changes are defined as long term or irreversible modifications along the time arrow of system's configuration, including boundary conditions, input data, 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-economical sciences and geosciences in general.

6.3 Keywords

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

6.4 Targets of the research activity

During the IAHS Scientific Decade 2013-2022, the research targets below will be pursued, by means of the Science Questions outlined in the Section 8.5

Target 1 – Observing and Understanding

Improve the observation, knowledge and understanding of hydrological systems, and in particular variability, indeterminacy, impacts of change, interaction with human activity. Special attention will be dedicated to new monitoring techniques, complex systems like mountain areas (glaciers), urban areas, alluvial fans, deltas and other systems interacting with society.

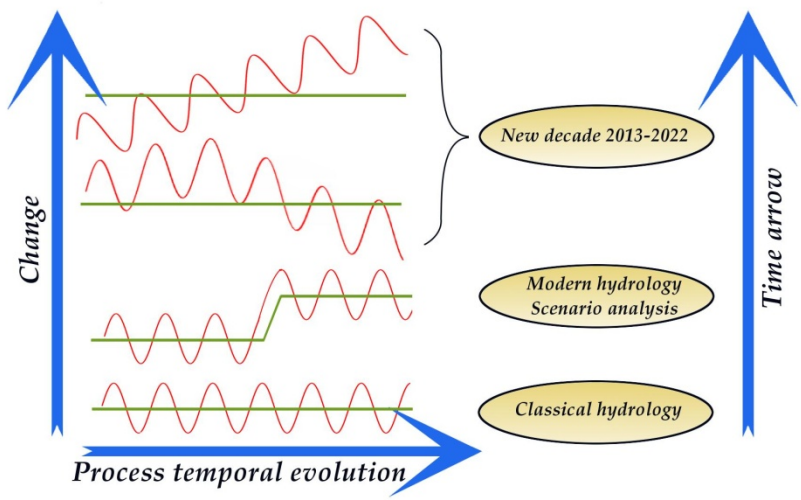


Figure 8. Progress of change treatment in hydrological sciences, from steady state in classical hydrological, sequence of steady-states in modern hydrology and long term changes and unsteady state in the future.

Target 2 – Estimation and prediction

Estimate and predict the behaviours and patterns of hydrological systems, with uncertainty assessment to support risk evaluation. This target includes estimation of design variables under change.

Target 3 – Science in practice

Address societal needs, policy making and implementation.

6.5 Science questions

Science question 1 – referred to Target 1

SC1. How to understand the behaviours of changing hydrological systems?

How can patterns observation help us? How can co-evolution be modelled? How can we effectively bring together theoretical hydrology, experimental hydrology, applied hydrology, and new measurement techniques to advance our knowledge of hydrological processes?

How can the typical time scales of change be identified? How can we constrain change? How can we better understand hydrological behavior across different spatial scales?

Research themes

Understanding the behaviors of change is made complicated by the limited information we presently have on hydrological processes. The opportunities given by advanced monitoring techniques must be investigated, to gain a better comprehension how natural systems are changing, and in particular climate and weather. Moreover, a deeper insight is necessary on how natural systems react to changes. There is no question that climate is rapidly changing, but the comprehension is still limited of its actual variability in the long and short term, and there is still little understanding of catchment's reaction to change. A negligible change in climate may translate in a dramatic change of water resources availability and quality. Currently knowledge on climatic impact is still very limited (Bloeschl and Montanari, 2010; Koutsoyiannis et al., 2009)) and mainly based on scenario analysis, which suffers from relevant uncertainty in the definition of the future climatic scenarios and hydrological modeling.

Research activity is needed to better inspect catchment functioning and climatic impacts, by bridging experimental and theoretical hydrology. A more extensive analysis is needed on the co-evolution of hydrological, geomorphologic, chemical and ecological systems, therefore advancing the classical view that treats the catchment as a fixed entity and interacting systems as static entities or boundary conditions. It is of paramount importance to better understand the variability of hydrological processes and its interaction, with possible resonance, with the variability of related systems.

To implement the above research, data are fundamental. Data sharing and open data access are key means to improve the current knowledge.

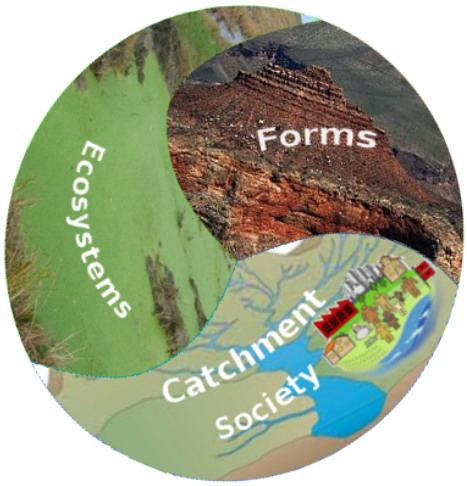


Figure 9.interactions among ecosystems, forms, hydrology and society.

Science question 2 – referred to Target 2 and Target 3

SC2. How to integrate advanced knowledge with indeterminacy modelling and uncertainty assessment for improving prediction?

How to combine prediction and uncertainty assessment in a coherent framework that features uncertainty as an intrinsic attribute of hydrology and not a limitation? How to use co-evolution and self-organisation laws to improve prediction?

Research themes

Relevant progresses have been made in uncertainty assessment and modeling in recent years. However, uncertainty in hydrology still remains very relevant, being also an expression of internal variability and indeterminacy. A paradigm shift is needed in the treatment of uncertainty, which needs setting up a coherent theoretical framework for uncertainty assessment and modeling. Such a framework should recognize (and therefore promote) the opportunity to reduce uncertainty by improved understanding (reduction of epistemic uncertainty) while also recognizing that randomness might be a distinguishing feature, rather than a limitation, of hydrological sciences as it is for thermodynamics.

An improved communication with end users is urgently needed to better convey the meaning of uncertainty and indeterminacy, and its treatment when applying science in practice.

Science question 3 – referred to Target 3

SC3. How can we produce sound and transparent scientific modeling tools (open source)?

How to develop estimation/prediction methods that are based on good scientific understanding but are also practical to apply on a routine basis by water resources

managers and engineers? How can we improve the packaging and dissemination of our knowledge? What are the critical requirements for an agreed protocol/standards for performance assessment and hypothesis/model testing? How can we effectively communicate uncertainty and risk to water resources managers? How can the hydrological community best listen to the needs of society as given by water resource managers?

Research themes

Open source modeling is the way forward to pursue a global involvement of the hydrological community to solve emerging problems related to water. Currently, software sharing is limited by the lack of identified protocols (best practices) in hydrological modeling, uncertainty assessment and model validation. The International Association of Hydrological Sciences should play a leading role in discussing the value of data sharing and virtual hydrological laboratories as shared working environment to support results sharing as a means to comparative hydrology into practice.

Science question 4 – cross-cutting targets

SC4. How can we initiate the development of new measurement techniques?

How to develop a vision to anticipate and maximise the monitoring technologies that will become available in a few years for the benefit of hydrology? What is the functional requirement for new monitoring systems? What is technically possible? How to make use of new information and communication technologies for scientific cooperation and sharing of multi-basin models, data, and codes? How to effectively combine the observations of the past with new observations based on new technology?

Research themes

Today, the availability of a massive amount of information (mainly produced by remote sensors) introduces research questions related to its use in hydrological modeling. It is clear that any kind of available information should be used in hydrology, but it is not as clear how the information can be used to improve knowledge. The next ten years will bring tremendous new opportunities to monitor environmental processes. A new generation of models and a paradigm shift are urgently needed to make hydrology up to date with respect to newly available spatially distributed data. An integration of hydrological model with geographical information systems, within virtual water laboratories, is an interesting way forward.

Science question 5 – cross-cutting targets

SC5. What are key actions to get connected with society?

Enabling research

An efficient interdisciplinary effort requires setting up links with society, which means links with social sciences, decision makers and end users. A key issue to reach

this goal is to develop research themes that address human needs. However, a paradigm shift in our research activity is also needed, to make hydrology really interdisciplinary. IAHS may play an effective role to this end through its commissions and national hydrological associations.

More Science Questions to be added basing on input from the community

Proposals so far:

Science question: water ethics: Are the current principles of Integrated Water Resources Management sufficient to achieve the dual goals of meeting human needs while also preserving the environment? (D. Garen, IAHS Blog).

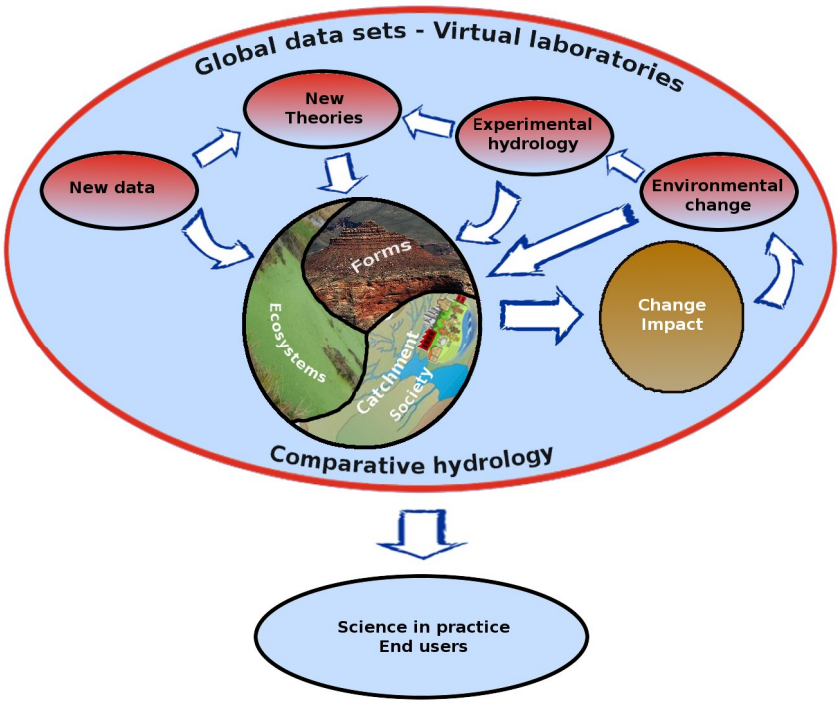


Figure 10. Research themes related to the study of changing environmental systems

7. 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 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 the Gothenburg Assembly.

Note: the IAHS Blog received many suggestions for research themes. These will be defined in Spring 2013. A post will be open in the blog to collect ideas around February 2013. Bloggers are invited to continue to follow the discussion at:

http://distart119.ing.unibo.it/IAHS

8. Conclusions

To be written

9. Appendix – Definitions

Hydrological change

Hydrological change is defined as a long term (reversible or irreversible) modification of a hydrological system's configuration, including boundary conditions, input data, and internal dynamics.

Stochastic

Stochastic (from the Greek verb στοχάζεσθαι for shooting (an arrow) at a target and metaphorically guessing a target) is a term that refers to systems whose behaviour is intrinsically non-deterministic. A stochastic process is one in that the subsequent state of the system is determined both by predictable and random outcomes. The term "stochastic" is herein used to collectively represent statistics probability, and stochastic processes.

Indeterminism

Indeterminism is a philosophical concept according to which events cannot be determined by causality based on prior events. It is the opposite of determinism and it is related to chance. Indeterminacy involves randomness and uncertainty. However, these latter may be also caused by impossibility to mathematically describe a deterministic process, while indeterminacy strictly refers to lack of determinism. Therefore, the presence of indeterminacy means that a process may not only be impossible to describe deterministically but may be fundamentally not deterministic. The latter case has been fundamental in quantum physics, while the former is typically met in classical physics.

Stationarity

Stationarity applies to a stochastic process whose joint probability distribution does not change when shifted in time or space. Consequently, statistical parameters such as the mean and variance, if they exist, also do not change over time or position. Conversely, processes in which such parameters change in time in a deterministic (known a priori) manner, are called nonstationary. It is important to emphasize that change is not identical with nonstationarity. Even stationary processes change all the time, otherwise they would not be called processes.

Co-evolution

Co-evolution refers to systems that evolve together with a two ways interaction.

Definitions to be completed

10. References

Atkins, P., Four Laws that Drive the Universe, Oxford Univ. Press, 131 pp, 2007

Blöschl, G. and A. Montanari (2010)."Climate change impacts-throwing the dice? (vol 25, pg 374, 2010)." Hydrological Processes 24(8): 1094-1094.

Blöschl, G. and M. Sivapalan (1995). "Scale issues in hydrological modeling: A review." Hydrological Processes 9(3-4): 251-290.

Brundtland, G. H., and World Commission on Environment and Development: Our Common Future, Oxford University Press, 147 pp., 1987.

Cudennec C. and Hubert P. (2008). Multi-objective role of HSJ in processing and disseminating hydrological knowledge. Hydrological Sciences Journal, 53(2), 485-487, doi: 10.1623/hysj.53.2.485

Cudennec C., Leduc C. and Koutsoyiannis D. (2007). Dryland hydrology in Mediterranean regions–a review. Hydrological Sciences Journal, 52(6): 1077-1087, doi: 10.1623/hysj.52.6.1077

Di Baldassarre, G., Montanari, A., Lins, H., Koutsoyiannis, D., Brandimarte, L., Bloeschl, G., Flood fatalities in Africa: from diagnosis to mitigation, Geophysical Research Letters, 37, L22402, doi:10.1029/2010GL045467, 2010.

Dooge, J. C. I. (1986). "Looking for hydrologic laws." Water Resources Research 22(9): 46s-58s.

Dooge, J. C. I. (1988). "Hydrology in Perspective." Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 33(1): 61-85.

European Environmental Agency, Annual report 2011 and Environmental statement 2012, available on-line at http://www.eea.europa.eu/publications/annual-report-2011

Falkenmark, M. and M. Lannerstad (2005). "Consumptive water use to feed humanity - curing a blind spot." Hydrology and Earth System Sciences 9(1-2): 15-28.

Gupta, V., C. J. Duffy, et al. (2000). A Framework for Reassessment of Basic Research and Educational Priorities in Hydrologic Sciences Albuquerque, NM, Report of a Hydrology Workshop, Albuquerque, NM, Jan. 31- Feb.1, 1999, to the NSF-GEO Directorate: 40.

Harte, J. (2002). "Towards a synthesis of Newtonian and Darwinian worldviews," Physics Today, October, 29–34.

Hooper, R. (2009)."Towards an intellectual structure for hydrologic science." Hydrological Processes 23: 353-355.

Jackson, R. B., S. R. Carpenter, et al. (2001). "Water in a changing world." Ecological Applications 11(4): 1027-1045.

King, C. and M. Webber (2008)."The Water Intensity of the Plugged-In Automotive Economy." Environmental Science & Technology 42(12): 4305–4311.

Koutsoyiannis, D., A hymn to entropy (Invited talk), IUGG 2011, Melbourne, International Union of Geodesy and Geophysics, 2011, available online at http://itia.ntua.gr/en/docinfo/1136/

Koutsoyiannis, D., Montanari, A., Lins, H.F., Cohn, T.A., Climate, hydrology and freshwater: towards an interactive incorporation of hydrological experience into climate research, Hydrological Sciences Journal, 54, 394 – 405, 2009a.

Koutsoyiannis, D., C. Makropoulos, A. Langousis, S. Baki, A. Efstratiadis, A. Christofides, G. Karavokiros, and N. Mamassis, Climate, hydrology, energy, water: recognizing uncertainty and seeking sustainability, Hydrology and Earth System Sciences, 13, 247–257, 2009b.

Koutsoyiannis, D., Scale of water resources development and sustainability: Small is beautiful, large is great, Hydrological Sciences Journal, 56 (4), 553–575, 2011.

Kundzewicz, Z. W. (2007). Mathematical modelling of ecohydrological systems in the changing world. Wetlands: Monitoring, Modelling and Management. T. Okruszko, E. Maltby, J. Szatylowicz, D. Swiatek and W. Kotowski: 151-159.

IAHS BLOG (2012), A Science Initiative of the International Association of Hydrological Sciences, moderated by A. Montanari, http://distart119.ing.unibo.it/IAHS.

McDonnell, J. J., M. Sivapalan, et al. (2007). "Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology." Water Resources Research 43(7).

Milly, P. C. D., J. Betancourt, et al. (2008). "Stationarity is dead: Whither water management?" Science 319(5863): 573-574.

Milly, P. C. D., R. T. Wetherald, et al. (2002). "Increasing risk of great floods in a changing climate." Nature 415(6871): 514-517.

Montanari, A. and Koutsoyiannis, D., A blueprint for process-based modeling of uncertain hydrological systems, Water Resources Research, in press.

Postel, S. L. and A. T. Wolf (2001)."Dehydrating conflict." Foreign Policy(126): 60-67.

Röckstrom, J., W. Steffen, et al. (2009). "Planetary Boundaries: Exploring the Safe Operating Space for Humanity." Ecology and Society 14(2).

Sheffield, J. and E. F. Wood (2008)."Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations." Climate Dynamics 31(1): 79-105.

Schaefli, B., Harman, C. J., Sivapalan, M., and Schymanski, S. J.: HESS Opinions: Hydrologic predictions in a changing environment: behavioral modeling, Hydrol. Earth Syst. Sci., 15, 635-646, doi:10.5194/hess-15-635-2011, 2011.

Sivapalan, M. (Editor) (2011). Predictions under Change (PUC): Water, Earth and Biota in the Anthropocene. Draft Research Report. Center for Water as a Complex Ecosystem, University of Illinois at Urbana-Champaign. http://cwaces.geog.uiuc.edu/synthesis/reports/index.html.

Sivapalan et al. (2013), Predictions under change: water, earth, and biota in the anthropocene, Inter-Journal Special Issue of Hydrology and Earth System Sciences and Earth System Dynamics, edited by M. Sivapalan, T. J. Troy, V. Srinivasan, A. Kleidon, D. Gerten and A. Montanari.

Srinivasan, V., E. F. Lambin, S. M. Gorelick, B. H. Thompson, and S. Rozelle (2012), The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies, Water Resour. Res., 48, W10516,

doi:10.1029/2011WR011087.

Torgersen, T. (2006). "Observatories, think tanks, and community models in the hydrologic and environmental sciences: How does it affect me?" Water Resources Research 42(W06301): doi:10.1029/2005WR004466.

Vörösmarty, C. J., P. B. McIntyre, et al. (2010). "Global threats to human water security and river biodiversity (vol 467, pg 555, 2010)." Nature 468(7321): 334-334.

Vörösmarty, C. J., P. Green, et al. (2000). "Global water resources: Vulnerability from climate change and population growth." Science 289(5477): 284-288.

Wagener, T., M. Sivapalan, et al. (2010). "The future of hydrology: An evolving science for a changing world." Water Resources Research 46(W05301): doi:10.1029/2009WR008906.

Zhao, M., A. J. Pitman, and T. N. Chase (2001), The impact of land cover on the atmospheric circulation, Climate Dynamics, 17, 467–477.