

INTRODUCTION TO A SPECIAL COLLECTION

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Special Section:

The 50th Anniversary of Water Resources Research

Key Points:

- Legacy of hydrological sciences
- Future perspectives for hydrology
- A reference for young and future generations of researchers

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Fifty years of *Water Resources Research*: Legacy and perspectives for the science of hydrology

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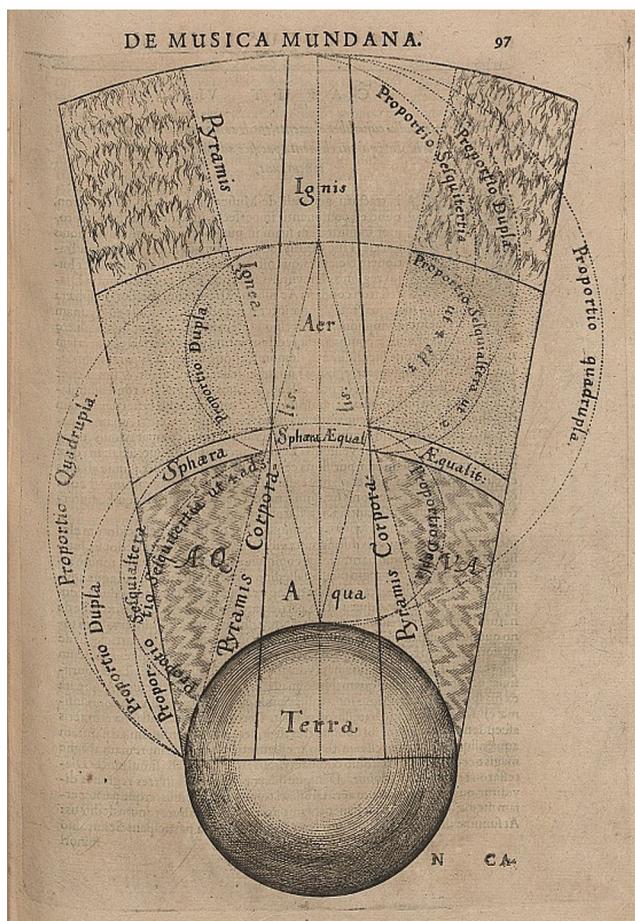
Abstract We present an overview of the contributions collected to celebrate the fiftieth anniversary of *Water Resources Research* along with a critical discussion of the legacy and perspectives for the science of hydrology in the 21st century. This collection of papers highlights exciting pathways to the future of water sciences. New monitoring and modeling techniques and increasing opportunities for data and knowledge sharing from hydrological research will provide innovative means to improve water management and to ensure a sustainable development to society. We believe that this set of papers will provide valuable inspiration for future hydrologists, and will support the intensification of international cooperation among scientists.

1. Premise

Water science will play an increasingly important role for the benefit of humanity during the next decades, as water will be the key to ensuring adequate food and energy resources for future generations. It is well known that the interrelation between water and humans is as old as humans themselves. The ancient Greeks recognized water as one of the four essential elements (see Figure 1), and water is an essential part of Hinduism and Buddhism. Challenges associated with water have marked human history and will be more and more prominent at the global level in the coming years. The intensive environmental changes that are occurring over the planet are one reason for increasing concerns related to sustainability of the current development. Climate dynamics, ecological systems, biological diversity, and diseases of humans and other species are intimately related to water: alterations of the water cycle impact people and society by affecting their links with the overall Earth system.

The increasing pace of environmental changes calls for a better understanding of hydrology. It is well known that the total amount of freshwater on the Earth could potentially satisfy the actual and future human demand. However, the uneven spatial and temporal distribution of water resources results in insufficient water availability over large portions of the planet during several months of the year. The uneven distribution of water is responsible for insufficient food resources, conflicts, and eventually inequitable development that can stimulate widespread migration. Although the virtual water trade is offering the opportunity to more easily distribute water in space and time, through increasing connections between hydrology, economics, and politics, the above water problems are still unresolved.

With such a premise, it is not surprising that the discipline of hydrology, which is rooted in engineering to solve real water problems, emerged in the last 50 years as a primary field of geosciences. It is now called upon to integrate across an enlarged interdisciplinary water science with fields such as geography, social sciences, public health, engineering, and advanced monitoring technologies to solve an increasing number of water sustainability problems.



Quelle: Deutsche Fotothek

Figure 1. A diagram from Robert Fludd (1574–1637) showing the segment of the macrocosm with the elemental spheres of terra (earth), aqua (water), aer (air), and ignis (fire) (from Wikimedia Commons).

To address such scientific challenges, water science needs to develop a new vision in order to take best advantage of increasing computational power, new monitoring techniques, new opportunities for sharing information, and the exciting perspectives given by the tremendously enhanced international and interdisciplinary cooperation. Looking back in the past, one immediately realizes that most of today’s routine research methods could not have been developed 20 years ago, when current monitoring facilities were not available and the opportunities for cooperation and information exchange were much fewer than nowadays.

Realizing this new vision is an exciting challenge, requiring new theories, new methods, and, above all, new thinking, as well as the capability to proactively look at the future. The science of hydrology will lead such an endeavor, by capitalizing on its legacy and providing the means to look at water’s future with renewed motivation and excitement.

2. The Fiftieth Anniversary of Water Resources Research

The awareness of the above scientific challenges inspired the editors of *Water Resources Research* (WRR) to take the exciting opportunity given by the fiftieth anniversary of the journal to promote an international endeavor for shaping innovative perspectives on the future of water science for people. The first issue of WRR was published in March 1965. During the past 50 years, WRR has promoted the growth of hydrologic science by defining new cutting-edge research, contributing to the solution of important open problems, and acting as a catalyst for interdisciplinary research. In the past five decades, hydrology has

emerged as a central discipline of Earth science. The amount of knowledge that has been gained is enormous; many new avenues of research have opened to address water problems and to develop the necessary knowledge. The milestone of the fiftieth anniversary of WRR is an occasion to reflect on 50 years of research activity and anticipate the exciting future where hydrologists will play a fundamental role to improve our knowledge of the Earth system, the climate, and water resources as vital elements for the benefit of humanity.

An open call for contributions was issued to generate a brainstorming activity and the synthesis of forward looking ideas. The resulting collection of papers is an ideal follow up of the special issue Trends and Directions in Hydrology, that was edited by Steven Burges in 1986 to celebrate the twentieth anniversary of WRR [Burges, 1986]. Trends and Directions in Hydrology is still a milestone, providing useful references for both young and senior hydrologists. The ambition of the current editors of WRR is to offer a similar inspiration for the current and future generations of hydrologic scientists by presenting an outstanding collection of papers to celebrate the fiftieth anniversary of WRR. These papers provide an overview of the most advanced research in water science.

3. Structure of the Special Section and Overview of the Contributions

The collection of contributions dedicated to the fiftieth Anniversary of Water Resources Research is organized in three chapters:

1. The legacy of hydrological sciences, which includes 12 papers.
2. Water processes interpretation and modeling, including 21 contributions.
3. Water resources, society, and water threats, including 23 papers.

Contributions are also indexed according to a classification of their main subject. The following subject areas were identified:

1. Critical zone and ecohydrology (6 papers).
2. Fluvial systems and hyporheic zone (10 papers).
3. Global hydrology, change and human impact (7 papers).
4. Groundwater flow and contaminant transport (5 papers).
5. Groundwater resources (6 papers).
6. Overarching principles, theories, and methods (12 papers).
7. Vadose zone hydrology (2 papers).
8. Water resources and risk management (8 papers).

From the above list of chapters and subject areas, readers will recognize the emerging issues in modern hydrology. We offer below a short review of each contribution, which makes clear that the framework of the science of hydrology is quickly evolving through a change of scales. The attention of researchers is rarely dedicated to the single process or the single site; the focus is shifting from local to global spatial scales, from short to longer time scales, from individual hydrologic processes to an integrated analysis of the water cycle, with increasing interdisciplinary connections and international cooperation among researchers.

The first chapter, "The legacy of hydrological sciences," presents a collection of review papers on key subjects synthesizing past achievements and establishing the basis for future research. *Rajaram et al.* [2015] provides an overview of the history of WRR and its development along its 50 year life. *Cardenas* [2015] presents an historical view of hyporheic zone hydrology while *Binley et al.* [2015] document how geophysical methods have emerged over the past two decades to elucidate shallow subsurface processes. They also offer a vision for future developments in hydrogeophysics. *Brooks et al.* [2015] review recent work in catchment hydrology linked to hydrochemistry, hydrogeology, and ecohydrology. They highlight the significant knowledge gap in quantifying partitioning of precipitation in the critical zone. Reviews of advances in snow hydrology, physically based hydrological modeling, organic contaminant transport and fate in the subsurface, and colloid transport through saturated porous media are offered in papers by *Sturm* [2015], *Paniconi and Putti* [2015], *Clark et al.* [2015], *Essaid et al.* [2015], and *Molnar et al.* [2015]. *Kitanidis* [2015] reviews key ideas related to heterogeneity, uncertainty, and scale in subsurface flow and transport, and *Bras* [2015]

presents a commentary reflection on the research carried out by the author's group in the last decades. Finally, *Burt and McDonnell* [2015] highlight and review a selection of field-based papers and show how field scientists have sometimes posed strong hypotheses and approaches.

The chapter "Water processes monitoring, modeling and interpretation" presents a collection of contributions focusing on innovative ideas, principles, and methods. These contributions offer new perspectives for improving our knowledge of hydrological systems and processes. *Fan* [2015] discusses the role played by groundwater in the critical zone to shape large-scale patterns and processes. *McKnight et al.* [2015] present ideas about future directions for integrating real-time data with real-time modeling of biogeochemical processes in stream ecosystems. *del Jesus et al.* [2015] discuss point rainfall statistics derived from satellite rainfall measurements. *Church and Ferguson* [2015], *Savenije* [2015], *Bertuzzo et al.* [2015], and *Keylock* [2015] focus on river morphology, river estuaries, and fluvial fluid mechanics, while *Runkel* [2015] and *Hipsey et al.* [2015] direct their attention to stream hydrodynamics and aquatic ecosystems, respectively. *Harvey and Gooseff* [2015] concentrate on rivers, looking at how small-scale physical drivers link to larger-scale fluvial and geomorphic processes and ecological consequences. *Lettenmaier et al.* [2015] provide an overview of the innovative opportunities offered by remote sensing in hydrology, while *Lundquist et al.* [2015] comment on data errors and their detection. *Troch et al.* [2015] discuss catchment coevolution, while a global perspective is provided by *Bierkens* [2015] and *Roderick et al.* [2015]; the former focuses on the state, trends, and directions of global hydrology, while the latter discusses interpretation of climate model projections related to future aridity and consistency with geological observations. *Porporato and Calabrese* [2015] present a novel theory to include the probabilistic effects of random rainfall inputs to the age distributions of water in hydrologic systems, while *Condon and Maxwell* [2015] examine the role of topography as a driver of groundwater flux and water table depth. Vadose zone hydrology is the subject of the contributions by *Vereecken et al.* [2015] and *Or et al.* [2015]; the former paper presents the potential of novel technologies in advancing our understanding of soil hydrologic processes; the latter discusses the applicability of the Richards equation for capillary flows. Modeling of solute transport in heterogeneous aquifers and porous media is the subject of the contributions by *Fiori et al.* [2015] and *Ciriello et al.* [2015].

The final chapter, "Water resources, society, and water threats," deals with the water-humans nexus, which is becoming more and more important in view of the impacts on the water cycle from human-induced environmental changes. *Ceola et al.* [2015] present an analysis of the human pressure on water resources at the global level, while *Cosgrove and Loucks* [2015] offer new perspectives on water resources planning and management under a changing environment. Water security is the subject of the study by *Wheater and Gober* [2015], who propose that the human dimensions of water systems must be integrated into traditionally physical-based water science research. *McLaughlin and Kinzelbach* [2015] consider options for achieving food security in a sustainable way and estimate associated demands for water and land. *Kumar* [2015] focuses on hydrocomplexity, proposing a conceptual framework to integrate discovery science and engineering, observational and information systems, computational and communication systems, and social and institutional approaches to support novel and holistic solutions for water security. *Lund* [2015] offers a review of the scholarly and practical successes in integrating social and physical sciences for water management in contemporary times, while *Sivapalan and Blöschl* [2015] present a coevolutionary view of hydrologic systems, revolving around feedbacks between environmental and social processes operating across different time scales. *Vogel et al.* [2015] document that water, climate, energy, food, industry, society, economy, and environment are inexorably intertwined, arguing that understanding of human footprint in physical processes and the long-term coevolution of their states is needed for sustainable development and resilience. *Brown et al.* [2015] present a review of the history of water resource systems analysis from the Harvard Water Program developed in the 1960s, through its continuing evolution toward a general field of water resources systems science. *Hornberger et al.* [2015] assemble and analyze a large database for U.S. cities to gain a better understanding of the characteristics that lead to a transition to higher levels of water conservation. Water, agroecosystems, and agricultural landscapes are the subject of the contributions by *Porporato et al.* [2015], *Foufoula-Georgiou et al.* [2015], *Assouline et al.* [2015], and *Mande et al.* [2015]. *Richey et al.* [2015] focus on the estimation of groundwater stress at both regional and global levels. *Gambolati and Teatini* [2015] provide an overview of geomechanics linked to hydrologic processes as it has been developed and applied to predict major effects including anthropogenic land subsidence and ground uplift over the last 100 years. A review the current state

of geologic carbon storage in deep saline aquifers is offered by *Celia et al.* [2015], while *Tsang et al.* [2015] analyze the key hydrologic issues involved in underground nuclear waste repositories. *Gorelick and Zheng* [2015] present an overview of the impact of global change on groundwater management, while *Birdsell et al.* [2015] offer a review of modeling results on the contemporary issue of hydraulic fracturing. *Wohl et al.* [2015] present a comprehensive review of river restoration and elaborate a future perspective, while *Doyle et al.* [2015] propose to combine the influences of science, regulations, economic constraints, market demands, and intangible social expectations from other practitioners for stream restoration. Finally, *Merz et al.* [2015] discuss the role of surprise in flood risk assessment and management.

4. Future Perspectives

The contributions presented herein clearly point out emerging ideas and ways forward for the progress of hydrology. In particular, the following messages clearly emerge.

1. New monitoring techniques, and in particular, remotely sensed data, are offering exciting opportunities for observing hydrological processes across a wide range of spatial and temporal scales. New ideas and models are needed to profit from ever increasing information.
2. Global-scale modeling is offering exciting opportunities for gaining a comprehensive understanding and mapping of water resources availability and water threats. Although uncertainties in global-scale modeling are still a challenge, they are reduced by growing global data sets; therefore, working on larger spatial scales offers new ways forward to resolve global water problems.
3. The study of coevolution of hydrologic processes may provide new basis to gain a better understanding of system behavior and possible future scenarios.
4. Characterizing heterogeneity and quantifying its effects are an emerging challenge to gain a better understanding of hydrological processes.
5. The interaction between human and water systems needs to be analyzed from new perspectives to develop a comprehensive picture of the inherent feedbacks and coevolving processes and scenarios.

By looking at the above messages, one clearly sees that the working framework for hydrologists in 2015 is distinct from that depicted by the special section Trends and Directions in Hydrology that celebrated the twentieth anniversary of *Water Resources Research* [Burgess, 1986]. The traditional branching of the science of hydrology into subdisciplines, each focusing on a narrow portion of the water cycle, has given way to vibrant interdisciplinary hydrologic research tradition that focuses on a wide range of spatial and temporal scales, and interactions between water, earth, and biological systems.

The target for hydrology in the 21st century must be ambitious; there are relevant and global water problems to solve, there is a compelling need to ensure sustainable development of the human community. Our desire is that water science may evolve by gaining the necessary knowledge to address the scientific challenges posed by our era. Our hope is that water science may evolve at the global level, to minimize inequalities between genders, across the continents, and across the ethnic groups. Water is a unifying element, and water science will be vital to ensure that humans and our planet coevolve sustainably.

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