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Evolution of hydrological sciences from dimensions of object, discipline and methodology

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Abstract

The evolution routes and development stages in hydrological sciences are summarised from the following three dimensions: research object, discipline and methodology, by means of the descriptive-explanatory-humanistic ideology. Modern technical breakthroughs and socioeconomic developments have promoted hydrology from *geographical hydrology*, *engineering or applied hydrology to water resources hydrology* in terms of the focus of research objectives or problems. It has been observed from the point of view of methodology that hydrological sciences go through *deterministic hydrology*, *stochastic hydrology*, *isotope hydrology*, *digital hydrology*, etc. Hydrological sciences in the context of discipline dimensions can be divided into three main categories: *physical hydrology*, *chemical/environmental hydrology*, *biological hydrology* including eco-hydrology and socio-hydrology, although there are overlaps between these due to the complex and intertwined water-related challenges facing the hydrological community and other geosciences. Humans have played a significant role in changing land uses throughout the world and therefore, socio-hydrology is an increasingly significant branch of the hydrological sciences. It can be seen from analyses that biological hydrology is a new approach to cope with global change issues, and a new frontier direction in the field of hydrological sciences. It can also be seen from dialectical analysis of the different stages in the evolution of hydrology, that new frontiers or directions requiring investigation, scientific recognition and technical innovation will continue to be generated in the field of hydrology. The 3-dimensional diagram of evolution routes of hydrological sciences may provide some ideas for *Panta Rhei*, the new IAHS Science Initiative 2013–2022 for hydrological research under changing human and environmental systems in the real world.

1 Introduction

The business of Hydrology is to solve the water balance equation (Dooge, 1986). Quantitatively, the hydrological perspective towards the study of the Earth's water is reflected in the water balance equation. Hydrology was defined as "the science that seeks to explain and quantify the water balance dynamics for any defined spatial scale (from a point to global) and temporal scale (from seconds to years) and their relationships with the *physical* and *chemical* transport of matter through the hydrological cycle and with *ecology*" (Lee, 1992). The role of the hydrologist is to integrate the findings of the other allied sciences to explain the dynamics of water balance over an area in any defined time period and to establish their relationships to the *physical*, *chemical* and *biological* environments. Those three *italicised* words in the previous sentence could be taken into disciplinary consideration for the evolutionary stages of the hydrological sciences.

In this paper, according to the descriptive-explanative-humanistic ideology, the authors summarise the evolution routes and development stages of hydrological sciences from the dimensions of research objective (or problem), discipline and methodology, respectively. Some thoughts or ideas will be provided for future directions of Hydrology, especially at the intersection of the evolution routes in terms of research objective, scientific recognition, and technical innovation in the field of hydrology. It seems to us that the 3-dimensional diagram of evolution routes of hydrological sciences gives support to *Panta Rhei*, the new IAHS Scientific Decade 2013–2022 (Montanari et al., 2013), focusing on "Change in Hydrology and Society" for hydrological research to cope with the changing human and environmental systems in the real world.

2 Remark on approaches of hydrology

There exists many approaches to solving hydrological issues, such as steady and unsteady solutions with respect to time, homogeneous and heterogeneous methods with

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respect to space, saturated flow and unsaturated flow, continuous and discrete means, analog and digital methods, analytic and numerical approaches, linear and nonlinear methods, deterministic and stochastic approaches, white-box and black-box methods, physically-based and conceptual approaches, lumped and distributed methods, empirical methods and theoretical formulas. Due to the very significant variations in systems, including atmospheric, geochemical, hydrological and ecological processes, and the ceaseless interaction among hydrosphere, atmosphere, lithosphere, and biosphere, the collection, processing and analysis of water-related information in such a complex system should be established on the basis of Geosciences. During the 24th IUGG Assembly at the University of Perugia, Italy, July 2007, the IAHS PUB Scientific Decade 2003–2012 resulted in the suggestion that hydrologists should move from fitting hydrological data to fitting catchment characteristics.

Generally speaking, an approach to hydrology, different from classical mathematical and physical methods (such as mechanics, thermotics or thermodynamics), was regarded as a simplified approach (such as Horton infiltration formula, rainfall–runoff correlation, unit hydrograph, Muskingum routing, rational formula). Although mathematical and physical methods were restricted in the application of hydrology because of complex initial and boundary circumstances, they would still be the criteria to judge whether an approach to hydrology is correct or not. For instance, the Saint-Venant equations are the theoretical basis of channel flood routing approaches. The routing approach is right (wrong) if (not) in accordance with the equations (Zhao, 1994).

The evolution of approaches of hydrology might be summarised as ranging from empirical approaches to theoretical ones. At the beginning, hydrologists were not in a position to completely understand the theoretical basis of an approach to hydrology, but it might be found later on. The approach to hydrology was empirical at the beginning and the physical nature of formulae or the physical meaning of parameters was understood later on. For example, the Horton infiltration formula would be an approximate solution of the Richards equation under specific conditions, and the unit hydrograph could be derived theoretically from linear system theory, such as the Nash-form IUH.

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Dooge (1988) pointed out that progress in the development of hydrological theory has been hampered by a fragmentation of the approach to the subject and by a failure of communication between those using different techniques. The deterministic approach and the stochastic one have too often been considered as rivals to one another rather than as complementary. In fact the two approaches have similar response functions (Dooge, 1988). Ren (1992) proposed the compatibility between two approaches in his thesis at University College Galway by comparing Bernoulli and Poisson processes in terms of probability distributions, specifically for the Nash-form IUH case (Table 1). It is recognised that deterministic and stochastic approaches have been combined together for hydrological forecasting (such as linear perturbation models, probabilistic forecasting of hydrological variables) and for the quantitative manifestation of hydrological uncertainties since the 1980s. Grayson and Bloeschl (2000) gave a typical example showing that a combined deterministic (by soil type) and stochastic (by soil hydraulic conductivity) pattern produced patterns of runoff occurrence that were most similar to the observed patterns in the tropical environment.

It should be emphasised that hydrological experiments have been of great significance with respect to the development of hydrological disciplines, e.g. Darcy's law and Dalton's formula were derived from experiment and observation. It is true that progress in the field of hydrology, including steps from empiricism to conceptualisation and scientificity, and from qualitative description to quantitative explanation, has much to do with experimental measurement. As a result of a very complicated water system under an ever changing environment, it makes sense to conduct experimental research in sensitive regions to understand the hydrological cycle, matter and energy equilibria and to recognise the eco-hydrological response mechanisms in a changing environment, and to estimate ecological flow for environmental demand in rivers covering various climatological and geographical zones.

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3 Evolution routes and stages

The development of science (or a scientific discipline) may be attributed to two driving forces. One is the curiosity of scientists, and the other is the demand from society. The development of hydrology is no exception. In different periods of social development, hydrologists have undertaken the task of solving water-related problems for the national economy and people's livelihood. Meanwhile the discipline of hydrology has advanced by means of theoretical application and practical verification. On the basis of the descriptive-explanatory-humanistic ideological system, three main routes of evolution in hydrological sciences may be summarised as in the following sections.

3.1 Object dimension

Firstly, according to the historical development of resolved practical water-related problems, hydrology has undergone three different stages: geographical hydrology, engineering or applied hydrology and water resources hydrology (Chen, 1987). In the very early years, hydrology had just been included in geography/geology, known as geosciences nowadays, thus carrying the imprint of geosciences. At the beginning, the content of geographical hydrology consisted of the scientific survey of some explorers, the journey diary of some tourists, etc., perhaps owing to the curiosity of scientists in the old days. Later geographical hydrology was mainly regarded as a branch of physical geography. Usually hydrology was considered as a component or element of physical geography over a catchment.

With the progress of science and technology, the ability to control and manage water was increasing. The appearance of hydraulic projects requires not just a description of hydrological phenomena, but also a prediction of hydrological variables. Engineering hydrology, also called applied hydrology, emerged as the times required, in response to the requirement of socioeconomic development. That is to say, the demand from society became the driving force of the discipline of hydrology.

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With the increasing impact of human activity on the water cycle, hydrological regimes have deviated from the original equilibrium value. Hydrologists need to deal with the negative effect of human water utilisation on the hydrological cycle, including quantity and quality. Chen (1987) proposed that hydrological sciences entered a new era of water resources hydrology. The tendency in the development of modern hydrology has been to investigate the quantity, quality, and potential energy of surface water and groundwater. Hydrologists will not only study the basic variation of natural hydrology and estimate the probable quantity of water, but will also provide the hydrological basis for optimal water use and the protection of water quality.

3.2 Discipline dimension

Hydrological sciences could be divided into three main stages from the dimension of discipline; physical hydrology, chemical/environmental hydrology, biological hydrology. Physical hydrology, as the first stage of the route of discipline evolution, aims to explore the physical laws of hydrology, focusing on quantity, e.g. precipitation, evapotranspiration, runoff, discharge and water level, including hydrometry, forecasting, hydrological prediction and operation. Then, chemical hydrology is to seek the chemical processes involved in the transport of matter through the hydrological cycle, focusing on quality. Therefore, this stage was also called environmental hydrology. The third stage refers to biological hydrology including eco-hydrology and socio-hydrology, aiming to understand/recognise the biological aspects, roles and functioning, focusing on life, including plants, animals, humans, food production, such as the BAHC Project and HELP programme implemented in the 1990s. It could be said that hydrologists have concentrated their attention on physical processes and chemical transport of water bodies over the past decades, and terrestrial and aquatic biotic characteristics, including humans, have become increasingly important in the field of modern day hydrology. Looking forward, it is obvious that people will be one of the biggest agents of change impacting hydrological systems. The world exists only in change and change occurs at all time scales. Humans are part of the changing nature of hydrology (Montanari et al., 2013) and thus, socio-hydrology, a new science of people and water (Sivapalan et al., 2012), would be regarded as a significant branch of biological hydrology. That is one reason why IAHS initiated the new IAHS Scientific Decade 2013–2022 with a focus on “Change in Hydrology and Society”.

3.3 Methodology dimension

It has been observed from the point of view of methodology that hydrological sciences go through *deterministic hydrology*, *stochastic hydrology*, *isotope hydrology*, *digital hydrology*, etc. Hydrologists are familiar with the former three terms. Here we just introduce digital hydrology a little more. It refers to digital integration/fusion with respect to multiple-sources (space-borne, air-borne and ground-based) spatiotemporal information on the basis of a digital basin platforms, making it possible for hydrologists to seek the basic law of the Earth’s hydrosphere, in-depth mixing between basic hydrological theory and applied hydrological technique, providing multi-scale and multi-element hydrological information not only for water-related sectors such as hydraulic projects, agriculture, forestry, environment, industries and transport, but also for the Earth’s systems such as atmosphere, geography, geology and ecology with water/energy flux or state variables (Liu, 2000; Ren and Yuan, 2006).

3.4 Relation among routes and stages

The evolution routes and stages of hydrological sciences are summarised in Fig. 1.

The following comments can be made regarding Fig. 1. *Firstly*, the early or junior stage on each route was the basis of the senior stages, while the senior stage was the development and extension of the earlier stage, so as to cope with new issues or new situations, or the outcome of new methods, approaches, measurement, tools, and new techniques. For instance the simulation of water quality has to be dependent on the accurate calculation of water quantity. *Secondly*, the different stages, even along the same route, can be intercrossed. For example, as analysed in Sect. 2, the deter-

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ministic and stochastic approaches are compatible under certain conditions, and have already merged together for current approaches to hydrological forecasting. *Thirdly*, it can be seen from the dialectical analysis among different stages along the routes that the intersection of the main routes will generate the frontier direction in terms of study objectives, scientific recognition, and technical innovation in the field of hydrology. *Finally*, digital hydrology, eco-hydrology and socio-hydrology are frontier directions in the field of hydrological sciences, and new approaches to tackle global change issues.

4 Suggestion for Panta Rhei decade

Climate change and increasing population, two driving forces in the dynamic earth at present, are converging to create a water crisis affecting people and the environment. Eighty-three per cent of the land surface of this planet has been modified by the engineering activities of humans, in most cases without any understanding of how the impacts of these modifications have changed processes in natural ecosystems, such as biogeochemical cycles and energy flows. Virtually all these modifications have had direct and indirect impacts upon disturbances of the water cycles, sometimes both locally and globally (Harper et al., 2008).

Landscapes have changed significantly in China in the last 20 years and the amount and rate of change have been greater here than elsewhere in the world due to the rapid economic growth in this period. It can be seen from the typical semi-arid example of the Laohahe basin of northern China (Liu et al., 2009; Yong et al., 2013) that human activities have played a dominant role in streamflow alteration. Predicting the response of hydrologic systems in a changing environment requires that the water cycle be considered as a complex, interconnected system that includes not just the physical but also the biogeochemical, ecological, and human subsystems whose interactions contribute to land-forming (i.e. structure-forming) and life-sustaining processes (Wagener et al., 2010). Because of such a need, IAHS launched the New Scientific Decade 2013–2022: *Panta Rhei* during the IAHS-IAPSO-IASPEI Joint Scientific Assembly in Gothenberg in July 2013. It contains three targets, viz. understanding, prediction and estimation; science in practice; and six science questions, so as to cope with the changing environmental system (Montanari et al., 2013).

We expect that the three-dimensional diagram of the evolution routes and stages of hydrological sciences, as shown in Fig. 1, would provide some thinking and support for dealing with those science questions of the *Panta Rhei* decade, particularly in the aspects of methodology and discipline. For example, based upon a platform of digital basin, the means of digital hydrology can help answer the 4th science question "*How can we use improved knowledge of coupled hydrological-social systems to improve model predictions, including estimation of predictive uncertainty and assessment of predictability*?", since such a coupled system definitely contains a huge amount of information.

In addition, the intersection among different stages along the main routes will help effectively link climatic, hydrological, and agricultural models with social and economic analyses. Hydrological processes include both deterministic and indeterministic components due to their variability in space and time, and diversity in pathways of the water cycle. Accordingly, the approach to hydrological modeling could be a combination of deterministic and stochastic methods, the organisation of deductive and inductive approaches. In this aspect, a good example was given for hydrologic synthesis across processes, places, and scales (Bloeschl, 2006) in terms of runoff prediction in ungauged basins (Bloeschl et al., 2013), as the milestone outcome of the past IAHS PUB Decade 2003–2012.

Processes and elements of the hydrological cycle have changed due to changes in both upper boundary (climate change) and lower boundary conditions (land-use/cover, population growth, water supply increasing, socioeconomic development). It may result in water-related disasters as well as hydrological risk (Ren et al., 2012). The desire for people to intrinsically integrate natural, economic and social processes (dynamic) over multiple scales of space and time is becoming stronger and stronger. One would like to know, where the problem is more serious and what factors cause these problems in the real world. For instance, what is the relationship between eutrophication and land-use change? What are the best measures for mitigation? What types of crops should be planted within a catchment, so as to achieve both a maximum benefit in agriculture and to exert a minimal impact on water quality at the same time? To what extent might ecological property be deteriorated in the organised case of hydrological regimes and water quality which have changed? Answers to these questions requires a new approach such as eco-hydrology to balance water for humans and nature (Falkenmark and Rockström, 2004), and to check or review human socioeconomic activities. Additionally, digital hydrology may be capable of providing a new platform for a distributed framework and information integration (Liu, 2000).

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Table 1. Comparison between Bernoulli and Poisson processes in probability and the Nash-form IUH in both discrete and continuous cases.

Process type	Bernoulli (discrete) process	Poisson (continuous) process
Number of successes in m trials or outcomes occurring	Binomial distribution	Poisson distribution
Number of trial to 1st success or 1st outcome occurring	Geometric distribution, in accordance with the unit impulse response series (derived by Z-transform) of a single linear reservoir system in the discrete case	Exponential distribution, in accordance with the unit impulse response function (derived by *Laplace*-transform) of a single linear reservoir system in the continuous case, i.e. Nash-form IUH for the case $n = 1$
Number of trial to nth success or nth outcome occurring	Negative binomial distribution, equivalent to the discrete unit response series of n equal-reservoir cascaded system	Gamma distribution, equivalent to the Nash-form IUH in the continuous case of n linear reservoir cascaded system

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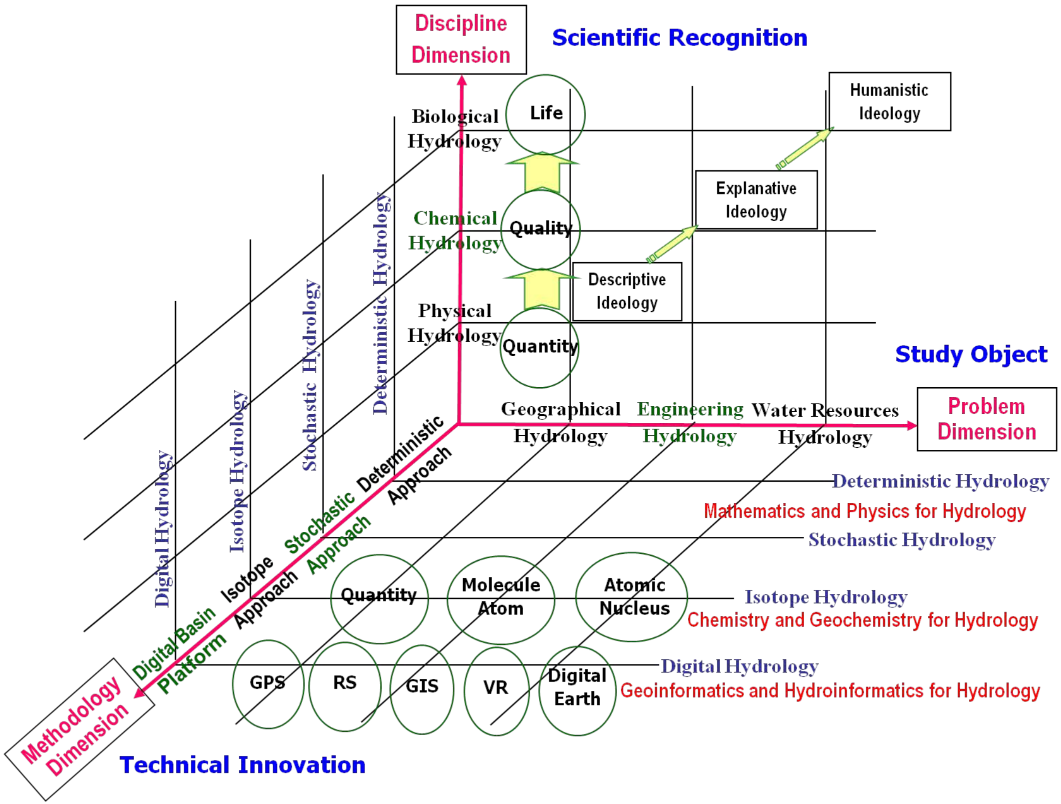

Figure 1. Three-dimension diagrammatic representation of the evolution routes and stages of hydrological sciences.

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