

Ecological-hydrological processes in arid environment: Past, present and future

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Abstract: Ecohydrology, aiming to study the interactions between terrestrial ecological systems and hydrological cycles as well as their impacts on water management, has been an emerging interdisciplinary research field since the 20th century. It hosts both natural and human regulated processes that are potentially coupled in complex ways. Understanding the ecological-hydrological processes, the fundamental mechanisms and the connections between them is critical since these processes are not isolated but integrated to impact basin-scale hydrological and biogeochemical functioning of a larger river system, especially in arid environment where water resources are considered to be the source of life. Thus, research on ecological-hydrological processes in arid environment is not only a scientific focus area but also important to sustainable development. Research projects and initiatives involved in observation, measurement, modeling and data assimilation have been well-developed for those purposes over the past 20 years. This review summarizes the historical development of ecohydrology science in China and the state-of-the-art tools available in the research framework. Five grand scientific challenges are listed as prospects and exciting opportunities for the scientific community. To advance the current ecological-hydrological processes research, scientists from multidisciplinary backgrounds (such as geography, geology, geomorphology, hydrology, geochemistry and ecology), need to unite to tackle the many open problems in new dimensions.

Keywords: ecohydrology; arid environment; observation; measurement; modeling; data assimilation

1 Introduction

The shortage of water resources has become a worldwide problem since the 20th century, which is directly related to environment, ecosystem and human living conditions, and even

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evolved into conflicts among countries or regions that suffer from severe water shortages. Governments and the scientific communities around the world have fully recognized the importance of fundamental research on ecological-hydrological processes and their impacts on environment and resources, which could essentially help planning and regulating water resources. In recent years, with the rapid development of water resources and ecosystem research, to integrate the ecological-hydrological processes at the basin scale starts to emerge as a multi-disciplinary research area that has been considered as “hot topics” in the scientific community. Such research aims to provide a solid scientific foundation for comprehensive management of river basin environment.

Over the past few years, resources and energy have become key factors for regional sustainable development. Water, as a multi-functional resource also serving as a medium and link in a variety of environmental processes, has attracted more public attention. In 2002, the World Summit on Sustainable Development (WSSD) held in Johannesburg, listed water as one of the top five topics in sustainable development, and emphasized the need to resolve the issues such as the relationship between water and development, correlation between water and environment, as well as water management and policy. Water resources, research and management at the basin scale have been integrated as a fundamental research unit to address such issues. Therefore, many countries have established regulatory agencies especially in those with drainage problems, such as the Tennessee Valley in the U.S., the Murray-Darling Basin in Australia, the Rhine Valley in Europe, etc.

One of the difficulties in basin-scale water resources research and management is how to ensure ecological water utilization under different conditions. It is well-known that ecological environment issues resulting from irrational human activities and overuse of resources make ecological protection more and more difficult. Therefore, it is necessary to establish a scientific and more profound understanding of the interactions between ecological and hydrological processes. The demand for basin-scale water resources research and management creates a favorable condition for rapid development of ecohydrology. To address the significance of ecohydrology in river basin management, UNESCO IHP (United Nations Educational, Scientific and Cultural Organization, International Hydrological Program) Phase-5 plan particularly defined the drainage basin as the research foundation to understand the macroscopic properties of biological and physical processes in large river systems, aiming to improve the management level of basin water resources. In 2007, UNESCO IHP Phase-7 plan listed river basin ecohydrology as a core research component in hydrology. Driven by the urgent needs of ecohydrological research, large-scale ecological-hydrological observation networks (e.g. European Network of Experimental and Representative Basins, ENERB; American Semi-arid Hydrology and Riparian Areas, ASHRA) have been established in many countries, which provides a solid foundation for understanding and addressing scientific questions related to river basin resource and environment (Vertessy, 2001).

China's inland river basins (1/3 of the country's land surface area) are mostly distributed in the northwest arid region, including Gansu, Ningxia, Qinghai, Xinjiang and western Inner Mongolia (Figure 1). The inland river basin plays a key role in China's agricultural, industrial and economic development. Therefore, ecosystem sustainability and protection has become critical in this region. However, in most of the inland river basins, the annual precipitation is less than 200 mm. 25 million people are living in scattered oasis (10% of the

entire arid area) with limited water resources (5% of the country's total amount). Under the influence of climate change, human activities and rapid economic development, desertification, salinization, dust storms and other ecological and environmental problems directly threaten regional sustainable development. It is obvious that the environmental crisis and future development problems of arid inland river basins are closely related to regional hydrology and water resources in the arid area of Northwest China (Wang *et al.*, 2003).

In order to solve the environment and ecosystem crisis, improve human living condition and sustainability in the Northwest region, statistics show that China has invested 40 billion RMB yuan in a series of strategic initiative projects that aim to protect the ecosystem and environment, which inspires further research on water resources and ecosystem science. Understanding the mechanisms and processes in water resources is the key to release the tension between water and ecology. Unfortunately, the current conflicts between water usage in life and industry and overuse of the oasis have resulted in severe ecosystem problems. One of the causes is that the research gap between water resources and ecosystem in arid area and limited understanding of the water-climate-ecology-economic system (Figure 1). Therefore, scientists in China need to promote associated research on integrated ecological-hydrological processes of inland river basins in arid environments, to discuss the water cycle in inland river basin and its response pattern under the environmental change and human activities, to explore the evolution of water resources, which are all closely related to China's economy and sustainability.

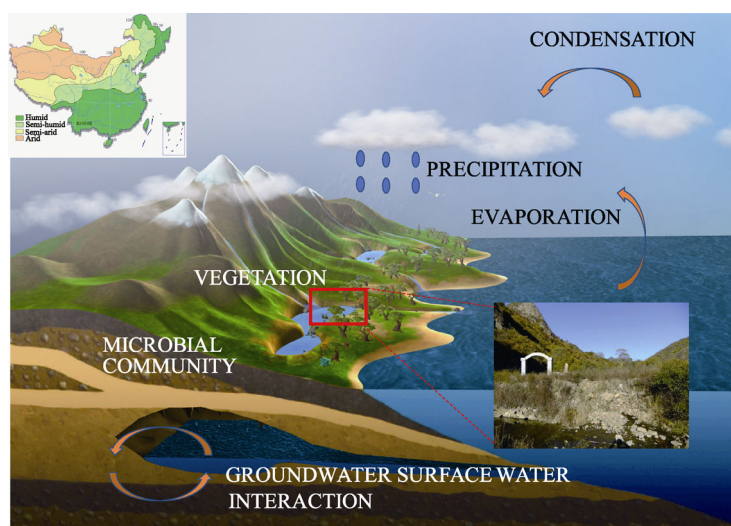


Figure 1 China's arid environment and coupled ecological-hydrological processes (generated and modified from resources on the internet)

In recent years, land surface system research has been nominated as an important component of the earth system science. The land surface system is a complex system that involves intrinsic links among various environmental factors. To incorporate those factors, an integrated research framework is essential to understand the interactions among water, soil, gas, life and human beings in the land surface system. Therefore, it is imperative to conduct multi-fidelity, multi-physics, multi-scale and multi-component research and eventually to

form a systematic research framework. Several countries have established corresponding research programs, such as the Coupled Human and Natural Systems (CHANS) supported by the National Science Foundation (NSF) in the U.S. China's arid inland river basin is a representative of such complex land surface system. With its clear boundaries, unique characteristics of the environment, significance of the water resources, it has naturally become an ideal platform for comprehensive and integrated research. China has initiated a series of research projects in the inland river basin since "The 11th Five-Year Plan" (2006–2010). For example, Chinese Academy of Sciences (CAS) has led the "Experiment and Demonstration of Water-Ecology-Economy Management in the Heihe River Basin" and "Action Plan for West Development Project "Watershed Airborne Telemetry Experimental Research (WATER)". The National Natural Science Foundation of China (NSFC) also proposed a number of projects that have achieved monumental results in ecological hydrology, ecological restoration, isotope hydrology and water environment, ecological economy and sustainable development, etc. Multiple digital river basin research platforms that integrate field observation, measurements, modeling frameworks and data assimilation tools have been built and demonstrated their capabilities to conduct integrated research on ecological-hydrological processes in China's arid environments.

This manuscript walks through the history of the basin-scale ecohydrological research in China, including reviews of the marvelous development, comments on the novel method/technology and proposals of the future perspectives. It will address scientific questions, inspire method/technology development, and provide a solid foundation of policy determination and management.

2 Ecological-hydrological processes research in arid environment

In this section, the review and current status of the arid area ecohydrological research will be summarized, which focus on the evolution of the research, key elements and associated projects and technologies.

2.1 A road map of ecohydrological research in China

A road map of the ecohydrological research is presented in this section following the philosophy of the "bottom-up" research, which uses hydrological research as the basis, then moves to a more complex ecohydrological system, followed by the transport processes as the key scientific questions and the observation-measurement-simulation framework, ultimately the art of water management.

2.1.1 Hydrology and water resources in arid area

In recent years, the hydrological process research in arid area at the river basin scale has become the forefront in the international science community. Several research agencies and institutes have already launched projects with regional characteristics, such as the Hydrologic Atmospheric Pilot Experiment in the Sahel (Hapex-Sahel), the Semi-Arid Land-Surface-Atmosphere Program (SALSA) and the Heihe River Basin Field Experiment (HEIFE), etc. The SAFRA program, implemented by the U.S. National Science Foundation (NSF) in 2000, focused on three aspects: river basin-scale water flux balancing, river networks and integrated modeling, which emphasized multi-disciplinary interactions in hydrology,

drology, regional model integrated coupling and river basin scale synthesis, so as to provide strong supports for the sustainable use of regional water resources. Supported by SAFRA, U.S. scientists conducted systematic studies on energy, water and solute flux exchange processes between groundwater, soil, permafrost, snowpacking, litter, canopy and atmosphere in the northern river basin, which completed a comprehensive observation, experiment and simulation study of the river basin.

Due to the spatial variability of hydrological variables, lack of data and the multi-scale nature of the hydrological processes, it is critical to solve, understand and recognize the hydrological processes and water resources formation processes via hydrological modeling. Lee *et al.* (2007) established the CREW hydrological model and proposed the theoretical derivation and simplified process analysis method of closure relation, which was successfully applied to rainfall, runoff and soil dynamics process forecast. Combined with detailed observation data, the ATFLOOD model is able to validate river flow, soil moisture, evaporation, snowpacking and groundwater flow (Bingeman *et al.*, 2006). The U.S. Department of Agricultural (USDA) and Agricultural Research Service (ARS) have developed a SWAT model that is capable of describing hydrological processes at the river basin scale, simulating surface and groundwater quality and quantity, and predicting the impact of land management practices on different soil types, land use patterns as well as large-scale hydrological, sediment and agricultural chemical production (Abbaspour *et al.*, 2007; Arnold *et al.*, 2000).

The development of digital river basin technology in this century has provided better technical support for river basin modeling. In the early 1980s, O'Callaghan and Mark (1984) first proposed the use of grid-based DEM to describe regional geomorphology and determine the direction of surface confluence and river network according to slope directions. Furthermore, the generated river network can be utilized to analyze watershed division, topographic features and confluence characteristics (Tarboton *et al.*, 1991). These pilot studies were adopted by geo-spatial analysis software such as ARC/INFO and ARCVIEW developed by Esri, which made distributed hydrological modeling more accurate and easier to implement. On the other hand, with the growth of the field observation technology, together with the surface observation data, larger surface environment database have been built in different regions, which accumulated extensive data on vegetation parameters, evaporation, soil moisture and surface temperature and so forth, creating better conditions for simulation, verification and validation.

The current crisis of ecological and environmental degradation in inland river basin of China has raised serious concerns of scientists and governments around the world. Scientists in China have carried out advanced research on hydrology and water resources of inland rivers, and made monumental achievements in recent years. Since 1999, the National Program on Key Basic Research Project (973 Program) has initiated a number of hydrology and river basin related projects, such as "Evolutionary Laws and Maintaining Mechanism of Renew able Capacity of the Yellow River's Water Resource", "Evolutionary Mechanism of Water Cycle and Efficient Utilization of Water Resources in the Haihe River Basin" and so on. Before that, a series of national key scientific and technological projects have successfully completed as well, such as "Predicting the Change Trend of Snow and Glacier and Runoff from Qinlin Mountain in the Heihe River Basin", "Water Resources Changes in the

Qilian Mountains and Water Transform in the Front of Mountainous Area in the Heihe River Basin". The National Natural Science Foundation of China (NSFC) also announced a major environmental and ecological research plan for Western regions during the 11th Five-Year Plan period. These studies have evidently enhanced the level of hydrological and water resources researches in China. Some highlights include:

- From the microscopic point of view, through the experiment and simulation study of moisture transport at the plant rhizosphere-leaf-air interface, the detailed mechanisms of the hydrological cycle in the air-soil-vegetation system is investigated with a better understanding.
- A multi-scale approach of quantitative analysis and dual hydrological cycle mode of water-ecology-economy linked by water has been proposed.
- The key role of human activities in the water cycle has been well recognized and studied.

Correctly recognizing and evaluating the impact of human activities on water cycling of the river basin is an emerging subject. Especially in some developing arid areas, human activities are becoming or have become one of the main drivers of the water cycle. The concept of binary hydrological cycle provides a theoretical basis for us to better understand the process characteristics of the water cycle. Through the comprehensive study of the water cycle, quantitative method of economic development and ecological protection is established, which also set up look-up tables and standards to help regulating the development and utilization of water resources in inland arid areas (Xia and Wang, 2001). Water resources allocation and management has also been pointed out by ecological economic scientists as the main research direction (Xia and Tackeuchi, 1999; Chen and Xia, 1999)

2.1.2 Coupled ecological-hydrological processes in arid area

Most of the inland river basins are located in arid areas, and extensive studies have found that the long-term drought environment has forced plants to form unique moisture transport processes to optimize water usage. For example, deep-rooted plants can drain deep soil water and even shallow groundwater to the rhizosphere of shallow root plants through the roots and release them into the soil for shallow root plants to absorb (Richards *et al.*, 1987; Schulze *et al.*, 1998). Some plants are able to rely on groundwater to resist drought environments, such as *Tamarix ramosissima* and *Haloxylon ammodendron* in the central Asian desert, whose different root functions depend the former survives due to groundwater, and the latter directly relies on atmospheric precipitation (Xu and Li, 2006). Some floras have unique anatomical structures and water metabolic methods to adapt to the high temperature and strong light conditions to obtain high biomass, such as desert plants *Haloxylon ammodendron* and *Calligonum* which possess the garland structure to fix CO₂ through C₄ photosynthetic pathway rather than C₃ which has considerably increased the water usage efficiency and productivity (Su *et al.*, 2004).

Banded vegetation and patchy vegetation are two major vegetation patterns in dry regions, and are fairly stable even under extreme events, which are the long-term results of ecological-hydrological processes in drought areas. In recent years, increasing attention has been paid to the study of hydrologically-controlled mechanism of ecological pattern, which is concerned with the effects of post-precipitation events of banded vegetation and inter-band soil to runoff and soil water residence characteristics. Researchers also focus more on direct

and indirect effects of soil water behaviors to vegetation productivity under different raining conditions. Based on the deeper understanding of ecological-hydrological processes, the conceptual model of triggering-transfer-reserve-pulse (TTRP) is advanced, which explains the ecological pattern of hydrological control in arid area (Ludwig *et al.*, 2004). In the inland river basins, typical forest ecosystems are well developed, of which the distribution is not only affected by precipitation and temperature, but also becomes more complicated due to the influence of mountain terrain effect. In the last decades, the neutral theory of ecology (Volkov *et al.*, 2003) suggests that the spread characteristic of plant species in the community determines the spatial distribution pattern of communities and ecosystems, which is a challenge to the traditional theories (Whittaker, 1972; Chave *et al.*, 2002). The study of ecological-hydrological processes may explain the rational application of the two theories by downscaling.

The water response of plants is the key problem of water cycle in the groundwater-soil-plant-atmosphere-continuum (GSPAC) system in the arid area. The application of the thermal pulse technology and other related technologies have already provided a basic understanding of the water transport process at different interfaces in the GSPAC, and also have gained preliminary knowledge of water consumption laws of plants below the individual or community scale. However, the recognition of feedback between land surface in arid area with little vegetation coverage and microclimate still remains at an early stage (Baird and Wilby, 1998).

The theory of landscape pattern and ecological process in landscape ecology plays an important role in ecohydrology. This theory can be also applied to different scales such as plots, slopes, watersheds, river basins, and regions. Landscape pattern is the basis of ecological-hydrological processes, so pattern dynamics can be a significant incentive for the evolution of such processes. The vegetation pattern in arid areas is mainly controlled by evident interaction between ecological and hydrological cycles. The dynamics of ecological-hydrological processes and landscape patterns are important research topics (Ludwig *et al.*, 2004). However, existing research isolates the ecological processes and hydrological processes, as ecologists emphasize the dynamics of vegetation patterns and updates (Montaña *et al.*, 2001) as well as plant productivity (Freudenberger and Hiernaux, 2001), while hydrologists tend to pay more attention to soil moisture balance, surface runoff and slope erosion processes (Galle *et al.*, 2001; Greene *et al.*, 2001). Nevertheless, the arid and semi-arid landscape is an ecologically-hydrologically coupled system that includes energy flux and interaction processes in both horizontal and vertical levels on diverse scales.

2.1.3 The problem of scaling

The scaling issue has consistently been a key aspect in the ecological-hydrological process research. It is necessary to solve the corresponding problem of hydrological scale and ecological scale in the spatial domain at different times. Data surveys must be performed both within the ecological and the hydrological scales, while the determination of this suitable scale requires multi-scale and systemic investigations. Landscape patterns and ecological-hydrological processes also find it difficult to confirm this scale. The landscape pattern is dominated by various factors at different scales that the climate characteristics and changes take the leading position when it comes to the large scale, yet the middle and small scales are more influenced by terrain and soil features as well as biological effects. The mechanism

of ecological-hydrological processes also varies with the scale. A large number of multi-scale ecohydrological observation plans have been started. The evaporation/transpiration process has been considered as a key research field, such as ABLE/CASES (Argonne National Laboratory Boundary Layer Experiment/Cooperative Atmosphere-Surface Exchange Study) launched together by National Oceanic and Atmospheric Administration (NOAA) and NSFC, German meteorological department's LITFASS- 2003, Lindenberg Inhomogeneous Terrain-Fluxes Between Atmosphere and Surface: a long-term study, EVA-GRIPS: The Evaporation at Grid/Pixel Scale, NOPEX: Northern Hemisphere climate-processes land-surface experiment initiated by the Scandinavian governments, and OASIS (Observations at Several Interacting Scales) sponsored by the Australian Research Council (ARC). In 2003, the German meteorological agencies carried out a heterogeneous surface grid (pixel)-based multi-scale evaporation/transpiration project, who applied micro-atmosphere flux station with field remote sensing equipment to obtain different surface flux data. The meteorological satellite was also adopted to collect surface flux data at the same time. Then researchers chose the soil-plant-atmosphere transmission model, the large-scale vorticity model and the mesoscale model to analyze the problem of evaporation/transpiration and scale coupling/conversion under heterogeneous surface (Cleugh *et al.*, 2005). Data obtained during the OASIS field observation program in Australia were also used to estimate the evaporation/transpiration in the area of 100 km² via the method of continuum boundary expenses. Denmead and Raupach explored regional scale evaporation/transpiration by means of aerial and surface observations (Beyrich and Mengelkamp, 2006). These studies all provide valuable experience in multi-scale ecohydrological research in the inland river basins.

In summary, understandings of ecological-hydrological processes from individual to multi-scales have thus been advanced, and there is also a better cognition of ecological-hydrological regulation mechanism of plant patterns in arid areas. All of these studies mentioned above have built the foundation for ecological-hydrological integration researches on inland river basins.

2.1.4 Vertical migration of water transport process and ecological modeling

In the process of studying the hydrological cycle and hydrological energy balance, people gradually realized that there is a big difference between the microscopic mechanisms and macroscopic properties in the hydrological cycle. Complicated properties are presented in different spatial scales in the aspects of precipitation, runoff and evaporation. The Soil-Plant-Atmosphere-Continuum (SPAC) system uses continuous, systematic and dynamic views and quantitative methods to analyze the physics and physiologic mechanism of the water transport and thermal energy transfer. As the focus for the hydrological study, vertical migration of water research focuses on the understanding of surface water, soil infiltration-evaporation/transpiration process and the groundwater hydrological process, as long as the exchange and interaction take place among them. There have been a group of hydrological models developed by scientists from different countries with alternative objectives, including the TopModel (Beven and Kirkby, 1979), SWAT (Arnold, 1993), SHE (Abbott *et al.*, 1986), MIKE SHE (Danish Hydraulic Institute, DHI), WEP (Jia *et al.*, 2001; Jia Y *et al.*, 2006), WATLAC (Zhang and Li, 2009; Zhang and Werner, 2009), VIC-Ground (Liang *et al.*, 2003), MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996), PGMS (Chen *et al.*, 2007), and GSFLOW (Markstrom *et al.*, 2008). All of the above hydro-

logical models acknowledge the coupled modeling and simulation framework for surface water, soil water and groundwater. For the vertical water migration of the single point, comprehensive mechanisms and processes as well as validations on the actual measured data have been established. For instance, researchers have built complete mathematical modeling systems for the field surface evaporation based on the balance and hydro-thermal simulation including snow melting and ice melting. The success of one-dimensional vertical migration simulation inspires the study on the vertical water migration developing from the single point to the regional scale.

Soil moisture is the most important parameter in water cycle. The most effective method for studying the soil moisture transport under complicated conditions is the numerical simulation method. The definition of unsaturated soil moisture kinetic parameter is the basis for the numerical modeling. Therefore, a precise definition of the kinetic parameter at river basin scale becomes critical. Large-scale analysis and prediction for the spatial distribution of soil parameter can be estimated by the digital elevation model combined with the regression analysis. The precision of soil hydraulic parameter directly affects the accuracy of numerical simulation results for the soil system (Van Alphen, 2001). In the aspect of soil water-groundwater interaction, an accurate unsaturated one-dimensional flow equation has been proposed (Lei *et al.*, 1982; Yang *et al.*, 1985; Kang, 1997). While the two-dimensional flow equation mathematical model is still under development (Zhang *et al.*, 1985; Yang, 1989; Yuan, 1990; Xu, 1997). Due to the complexity of the inland river basin, the numerical simulation of two-dimensional unsaturated flow is still being tested. Therefore, two-dimensional simulation of the soil water-groundwater transformation and moisture transport under the influences of the intermittent surface flow (caused by the human activities) needs to be further explored.

At the point scale, the soil water transport model based on the Richards equation has been fully developed from one dimension to three dimensions. Meanwhile, it has been coupled with the root growth model or the plant growth model to quantitatively describe the dynamics of the soil moisture and plant growth in the SPAC system in different ecological environments. On the basis of the hydro-thermal condition of the soil, it has modified the unsaturated equation for single-point soil depending on the field experiment. In recent years, in the inland river basin, the analysis on the relations among the soil moisture, vegetation density, productivity and diversification has been conducted. In the aspect of the patch scale of farmland or the ecological system, as the soil property features spatial variability, based on the soil water transport model at the point scale and the principle of geo-statistics, stochastic soil moisture transport model has been established to make quantitative analysis on the spatial-temporal dynamics of the soil water. At the river basin scale, it connects the closed relation between the point scale model with GIS, analyzes the moisture dynamics of soil under different soil utilization and coverage with the combination of the river basin hydrological model, eventually to define the optimal land utilization model of the river basin.

2.1.5 River basin ecological-hydrological observation network and data-modeling platform

Remarkable progress has been made to investigate inland river hydrological water resource process, ecological-hydrological processes at different scales, vertical water transport and exchange process, and ecological modeling. However, with the standardization of observation systems, the shortcomings in the aspects of dataset standard, quality control and model

platform construction still limit the further development of fundamental researches on process understanding, coupling mechanism and scale transformation, etc., which even become a bottleneck of developing decision support system for river basins. It is difficult to predict basin-scale hydrological process with global atmosphere and hydrological cycle models (www.ucar.edu), which are lack of both high-resolution remote sensing observations (Huntington, 2006) and field experiments, thus greatly influence the understanding of ecological-hydrological processes and modeling (Molotch *et al.*, 2005a; 2005b). Just as stated in the plan of U.S. CLEANER (Committee on Collaborative Large-scale Engineering Analysis Network for Environmental Research, National Research Council, 2006): “We are still unclear about how to design optimal observation networks and implement observations. We still lack the capabilities of comprehensive observations on hydrological and biogeochemical processes at river basin scale or larger scales under spatial and temporal contexts.” To improve the situation, CLEANER planned to build large-scale comprehensive environment observation networks. Water for Life 2005–2015 of International Water Commission also started to build water resources observation network and prepared to build a river basin monitoring system integrated with data collection, transfer and release. Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia Land & Water scientifically emphasized the data, simulation, software engineering and team strategies for future river basin research (Vertessy, 2001).

Chinese scientists also have invested great efforts on the construction of observation systems and have successfully executed a number of observation projects such as HEIFE (Heihe River Basin Field Experiment. 1989–1993), IMGRASS (Inner Mongolia Semiarid Grassland Soil-Vegetation-Atmosphere Interaction) and WATER (Watershed Allied Telemetry Experimental Research) (Li *et al.*, 2008). Through long-term observations, earth's energy and water balance, biochemical cycle in geographical environment, relations between biology communities/diversities and environment, landscape pattern and process have been studied. Significant achievements have been obtained by building an internationally advanced networked ecosystem observation system. However, so far, no comprehensive observation system targeting river basins has ever been built up, which greatly influences the research progress of ecological-hydrological processes at river basin scale.

2.1.6 Integrated river basin management research based on water-ecology-economic system

Development and management of water resources at the river basin scale have been accepted and introduced internationally. In 1968, European Parliament (EP) passed the European Water Charter, which clearly pointed out that the management of water resources shall not be limited by the management of administrative division, instead, to set up associated management organizations of water resources based on the river basin. Agenda 21, the United Nations Development Programme, passed by United Nations Conference on Environment and Development, made an overall explanation on the objective and task of river basin-based water resources management and emphasized that the objectives shall be altered in accordance with the socio-economic conditions of individual country.

In terms of sustainable development and optimal management of resources, scientists have developed frameworks of river basin water-ecological-economic systems research (Global Water Partnership, 2000). There are several milestones. Before the 1980s, river basin management mainly focused on hydraulic project, hydroelectric development and water

transport (Vertessy, 2001). After the 1980s and after Charles (1985) published *The Living River*, river basin research turned to the recovery of river way, ecological management of river, flood prediction, leisure planning and other comprehensive management. For example, Trukee River Flood Project in America has been continued since 2003, promoting the ecological management of river basin.

At the end of the 20th century, the concept of integrated river basin management was proposed by GWP, which paid special attention to establishing water resource management systems based on water right and theory of water marketing. Associated water policies and strategies were formed to improve the usage of water resources and promote coordinated development of economy, resources, and the environment. Integrated management of water resources of hydrology, ecology, and economy at the river basin scale participated by the public has reached the substantial stage of research. Integrated river basin management focuses on the management of water-ecological system and that of water-market. The former emphasizes the ecological value of water resources and pays close attention to ecological water utilization. Coupled approach of multi-scale methods and comprehensive analysis are adopted to investigate the relationship between the river basin ecological process and hydrological cycle, getting into the details of the mechanism in the soil-biological system and integrate systematized techniques of ecological recovery. Health management of ecological system and management of bio-diversity have become important topics. At the same time, the river basin water-ecological management is developed to include the market mechanism (Rockstriiml *et al.*, 2001). Together with administrative legislation, divisional management and division of profit, water-market management pursues the maximized river basin benefit. Water right and water price theory are used to adjust and control internal distribution efficiency of water resources. With the socialized management of water resources, the external distributional efficiency is improved. The issue of the shortage of natural resources is transformed into overcoming the shortage of social resources and attention is paid to the theory of public participation, technology and organizational patterns. Water cycle and water balance in the river basin water-ecological- economic system have and will become the most important factor (UNESCO, 2003).

Representative work of integrated river basin management includes: by the end of 2000, the EU implemented Water Framework Directive (WFD) which was committed to river basin planning, river way recovery and wetland protection carried out the integrated protection with the river basin as the unit; In river basin of Murroy-Darling River, Australia implemented privatization of water right of surface water and groundwater, combined agriculture, river and market, recovered intersected rivers through purchasing of water by the government. Different levels of management organizations (ministerial meeting, committee of the river basin and public consultation association) jointly ensured the equality, high efficiency and sustainability of water resources in the river basin (Kevin, 2003). However, after the development of half a century, the river basin management still lacks systematic management. Engineering management plays the key role, while ecological management is still in its initial stage. The market is quite premature. There is still no such an integrated river basin management model which can be applied to all countries, but we can objectively conduct research and analyze characteristics and advantages for certain river basin management and gradually establish and develop the theoretical foundation of river basin science on the basis of meeting the needs of its own country or river basin.

In 2007, the United States Geological Survey (USGS) submitted the first research plan of river basin science in the world (CRS *et al.*, 2007; MI, 2001). This plan summarized simulation and prediction of river basin process, environmental flows and river recovery, sediment movement and interaction of surface water and groundwater as prioritized fields of USGS and emphasized on river basin monitoring, data collection and other supporting systems.

China's river basin management organizations have played an irreplaceable role contributing and promoting economic development and social progress in river basins. China's current river basin management system of water resources was born in the planned economic system, thus having many congenital deficiencies. The socio-economic development, the gradual establishment of socialist market economic system, the transformation of traditional hydraulic engineering to modern and sustainable hydraulic engineering, and diversification of development, utilization and investment system and benefits pattern of water resources have brought opportunities, as well as a series of new problems and contradiction to the unified management of river basin resources. Besides, the legal construction, economic operational mechanism, ownership management of water resources in river basins and technical means of water resources management shall also be reformed and improved in light of requirements of socialist market economic system.

2.2 The current state-of-the-art on ecohydrology in China

2.2.1 Integrated research platform

In the research of ecological-hydrological processes in China's arid environment, there are three scientific focus areas: 1) evolution of the current environments; 2) role of human activities and regulation and 3) future development. In the last decades, with the support of China's top science and research agencies/institutes (e.g. National Natural Science Foundation of China, NSFC; Chinese Academy of Sciences, CAS), multiple integrated research platforms that aim to address the above issues have been established from both the engineering and scientific perspectives. For example, supported by NSFC's "Environment and Ecological Research in Western China", in China's northwest arid region, Loess Plateau region and the southwest karst region, four key research themes have been proposed: 1) evolution and development of China's western environment; 2) water cycle and sustainable usage of water resources; 3) ecosystem sustainability and 4) the impact of major constructions/projects on the environment. In addition, "Integrated Management of Water Resources in the Heihe River Basin" has been the key research project supported by CAS, which is targeted to improve water efficiency, to form an oasis farmland ecosystem and water management technology system, to develop the integrated irrigation water technology, to improve water resources management, to protect Juyan wetland and to help with the river basin water management and decision of associated policies.

A number of research teams and centers have then been formed to conduct scientific research in China's western arid areas. The Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI, CAS) has carried out nearly 20 years of ecological and environmental research work in Heihe River Basin (HRB). Detailed research includes hydrological circulation and water resources in typical urban areas, interaction between vegetation and water in the typical forest ecosystem, oasis ecosystem, desert ecosystem and alpine ecosystems. China University of Geosciences (CUG) has focused on the geological

formation, integrated modeling of the transport processes and mechanisms in groundwater and the hyporheic zone in Heihe River Basin. Institute of Ecology and Geography (IEG, CAS) has long been engaged in multi-scale ecological processes in arid environment. Both field observation and experiment have been conducted to investigate the mechanism of the interaction between water, vegetation and surface morphology in arid area. The impacts of human activities and regulations on macroscopic ecological processes were also studied. China Agricultural University (CAU) successfully established a three-dimensional root growth model and investigated the relationship between root growth and soil saturation of typical plant in arid area.

2.2.2 Observatory network and capabilities

Heihe River Basin is the main inland river basin in Western China, which has become a feasible field site for arid environment ecological-hydrological process research (Huai *et al.*, 2014). A comprehensive observatory network has been built through decades of efforts. A series of field observation sites covering typical landscapes and vegetation types have been selected and established in the network, which includes ice and snow permafrost zone, mountain forest vegetation zone, middle reaches of the artificial oasis and desert zone. Long-term observation on climate, soil, hydrological, biological and other environmental components have been and will be continuously conducted. Together with other meteorological stations in the Heihe River Basin, 75 operational hydrological stations, 41 regional stations and more than 50 groundwater wells. An integrated platform for meteorological, hydrological and ecological scientific research has thus been formed.

Based on the Heihe River Basin observatory network, “Watershed Allied Telemetry Experimental Research” has been organized and supported by both the CAS “Action Plan for West Development Project ‘Watershed Airborne Telemetry Experimental Research’ (WATER)” project and the national key basic research and development project “Land Surface Ecological Environment Elements Active Remote Sensing Collaborative Inversion Theory and Method”. The joint measurement is composed of cold area hydrological measurement, forest hydrological measurement, arid zone hydrological measurement and hydrometeorological measurement. The pilot period was from March to September in 2008, for a total of 120 days. More than 280 scientists, graduate students, engineers and technicians participated in the joint measurements during that period. For airborne remote sensing measurements, 5 types of airplane remote sensing sensor (L, K and Ka bands), laser radar, hyperspectral imager, thermal infrared imager and multi-spectral CCD camera were used during 26 flights in 110 hours. For field measurements, there were 12 reinforced and super automatic weather stations, 6 whirlpool-related flux stations, 2 large aperture scintillators and encrypted field observation network that involves multiple business weather stations and hydrological stations. The measuring equipments include rainfall radar, field-based microwave radiometer, field scatterometer and other large-scale remote sensing equipment and automatic observation instruments. Multi-scale measurements (river basin scale, key test section, encrypted and normal observation area) were designed to simultaneously and intensively collect snow parameters, permafrost parameters, soil moisture, surface temperature, reflectance and albedo, vegetation structure parameters, biophysical parameters, and biochemical parameters. In satellite remote sensing measurements, visible/near infrared, thermal infrared, the main passive microwave, laser radar and other satellite data were moni-

tored and collected.

CAREERI (CAS) has built a geographical information system named “Digital Heihe”, which includes fundamental geographical data (DEM, river basin boundary, administrative boundary, river network, road, etc.), remote sensing data (long-term sequence of AVHRR, MODIS; SPOT Vegetation data; medium resolution Landsat and ASTER data; high-resolution QuickBird data), basic observation data (meteorological, hydrological, groundwater and flux observations), joint field measurement data and other historical data (land use, geology and hydrogeology, groundwater hydrological depth, Heihe River channel section, distribution of irrigated area in the middle reaches of Heihe River, distribution of canal system and distribution of irrigation water in the middle and upper reaches of Heihe River). The collected and sorted data have reached 1TB, which has become the most complete and open-source database for basin-scale ecohydrological research.

3 Prospect for the future

Although we have made remarkable progress in ecological-hydrological processes research in arid environment, we are still facing grand challenges to advance our current understanding. Here, we propose 5 tasks to conquer listed as follows:

- To understand the influence of human activities on ecological-hydrological processes

- To understand the role of vegetation on the coupled processes and their multi-scale nature

- To reveal the ecological response pattern of the transport processes

- To establish an ecological-hydrological observation paradigm and data-model integration platform in arid area

- To improve the rational allocation of water resources in the basin and provide technical support for river basin integrated management

Challenge 1: While making significant progress in process research on hydrology and water resources in river basins of arid regions, we are in urgent need of finding the variation patterns of hydrology and water resources in complicated river basin systems under the influence of human activities.

Groundbreaking progress has been obtained in the field of hydrology as the remote sensing technology, geographic information system and isotope technology have been applied extensively in all areas. For example, in the Heihe River basin, a comprehensive inland river basin observation-measurement system that investigates the interactions among hydrology, soil, vegetation and atmosphere has been successfully established. A series of observations and experiments have been completed for flow and transport processes of water and species in layers of plant canopy, residuals, snow cover, frozen soil, and soil in typical river basin areas. Research on coupling of regional hydrological process and ecological process has been carried out, in which plant growth and vegetation coverage are taken as the objective functions, and functions of salinity conversion, soil factor, and meteorological factor taken as constraint conditions, with the hydrological process taken into consideration.

Challenge 2: On the basis that we have understood the influence of arid region vegetation on hydrologic process, and that of hydrologic conditions on ecological process, we are in urgent need of understanding the coupled mechanisms of hydrology and ecology, and multi-scale transformation mechanism.

There has been tremendous growth in both hydrology and ecology research over the past decades. The methods and technologies have certainly matured to describe the complex processes and mechanisms in either research field. However, now is the time to interplay the game by connecting those two correlated research fields and looking into the interactions in-between. There are three major issues to advance such efforts due to the complexity of the targeted study system, specifically in the arid environment: multi-scale, heterogeneity and uncertainty. At-scale research will be used to provide information and conservation laws. In terms of scale coupling, both top-down and bottom-up approaches are needed to integrate experiment, modeling and data.

Challenge 3: On the basis that we have understood and learned the process of hydrological cycle, we are in urgent need of discovering multi-scale models of ecological response to moisture transport and circulation.

The study on ecological effect of water transport is focused on integrated research and simulation of hydrology and ecology. During the process, not only physiological and ecological process of plants, optical energy efficiency need be considered, scaling (both temporal and spatial) is another important factor. For example, multi-spatial-scales could cover from pore, leaf, single plant, to global scale, which also connect multi-temporal scales that range from second, minute to year. The coupled dynamic model of soil water and plant growth could be utilized to make initial quantitative interpretation of the dynamic mechanisms of space-time evolution for vegetation distribution, as well as its correlation with precipitation or soil water. In addition, it is being applied in quantitative analysis of vegetation construction mode in continental river basins of arid regions. Although certain achievements of modeling for the moisture vertical movement exchange and ecological effect have been accomplished, we still know little about the mechanisms and processes in the groundwater-surface water interaction zone, and there is a lack of modeling theories on transport and transformation at the interface. Such gaps result in obscure understanding of the mechanism of moisture vertical movement. Especially in the cases involving regimes where surface water and groundwater do not directly interact due to the aeration zone in-between. The variably unsaturated aeration zone could range from tens to hundreds of meters, leading to hysteresis effect of the interaction between surface water and groundwater. Hence it is difficult to understand and simulate the transport processes under various situations.

Challenge 4: On the basis that we have acquired a large amount of long-term, ecological and hydrological observation data, we must establish normal forms and a model integration platform for ecological-hydrological observation in river basins of arid regions.

With the application of digital information processing, computational simulation and computing resources, with the help of the two classical and traditional research methods, i.e., theoretical analysis and experimental observation, multi-fidelity, multi-scale and multi-physics research framework becomes feasible., which can manage and describe long-term, distributed and static data effectively, establish a database to manage river basin data, data format, quality control, data exchange format and metadata conversion, create tools for data preparation, fusion, mining, discovering, and visualizing, and construct an assimilation system for land data, real-time multi-source remote sensing data fusion to generate high-quality datasets with high resolution and time-space consistency, so as to guarantee that scientists

could share and cooperate with each other in a cross-time, trans-regional, trans-departmental and even interdisciplinary manner.

Challenge 5: Under the guidance of research approach of river basin water-ecology-economy system, we must improve the ability to allocate river basin water resources rationally, and provide technical support to river basin integrated management.

To solve the emerged ecological environmental problems, scientists expect to conduct an integrated approach. Firstly, we need to focus on river basin-scale hydrological processes, and further understand the ecological environment function of river basin hydrological system as well as the relation among hydrological process, ecological process and economic process. Meanwhile, we need to explore detailed connections between multi-scale ecological process and hydrological cycles. An observation-measurement-modeling platform is essential to investigate the water, ecology, and human system. Although we have made great progress, there is still a lack of recognition of the general operation law of river basins since river basins are a dynamic, unbalanced, open, and “unstructured” or “semi-structured” system, which makes it tremendously difficult to conduct scientific management on river basin water resources. Therefore, we need to have profound understanding of the variation patterns of the water-ecology-economy system at the river basin scale.

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