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PREFACE

Preface: Groundwater sustainability in fast-developing China

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Introduction

China, with only about 5–7% of global freshwater resources, largely depends on groundwater to meet the domestic, agricultural and industrial groundwater needs of about 20% of the world's population (Qiu 2010). Excessive groundwater exploitation and intensive human activities have caused depletion of the reservoirs at an alarming rate in northern and northwestern regions, contamination of groundwater resources across the country, and a series of ecohydrological and environmental problems, which have drawn nationwide attention from the public, the government and academia.

Groundwater extraction increased by about 2.5 billion m^3/year in the past few decades of fast economic development; consequently, groundwater levels in northern and northwestern regions have greatly dropped. Water scarcity has become an increasingly serious problem for two-thirds of China's 660 cities (Qiu 2010). Groundwater contamination has become a major challenge, most serious in northwestern and northern China where the groundwater resources are in severe shortage. In southern and southeastern China, where the economic growth rate has been greater, groundwater is now laden with heavy metals and various contaminants.

Intensive human activities related to groundwater abstraction alter groundwater flow paths and affect its quality. Large-scale water conservancy projects built across China such as the South-to-North Water Diversion Project (SNWDP), may impact groundwater systems. As a result of these changes in groundwater flow systems, relevant ecological and geo-environmental problems have been observed, posing a threat to sustainable development. As China's economic growth continues, so will its demand for water. In view of this, the effect of quick economic growth on different aspects of groundwater systems should be monitored, understood and predicted for better groundwater protection and management. The effect of large-scale water conservancy projects on groundwater systems should be investigated for sustainable water resource management.

To help address the aforementioned issues, this special issue is intended to provide an updated summary of the recent advances in hydrogeological studies in China, to share the lessons with hydrogeologists in other countries that have been experiencing (or will experience) similar situations of fast development, and to encourage discussion on how to manage the precious groundwater resources for our common future in a global perspective. The content of this issue is summarized in the following.

Review of the evolution of groundwater systems under the impact of climate change and human activities and related environmental problems

To understand the state-of-art of hydrogeology research in China, **Wang Y. et al.** provide a general review of the evolution of groundwater quantity and quality affected by the rapid economic development, as well as resulting ecological and geo-environmental effects during the last several decades. This study stresses the importance of effective governance of groundwater resource management to ensure the ultimate goal of a safe and sustainable supply of groundwater in China.

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The specific information on distribution of groundwater exploitation and its induced environmental problems are important to fulfill the goal of a water sustainable supply. As such, **Hao A. et al.** review the regional hydrogeological conditions, the temporal and spatial distribution of groundwater exploitation and utilization, and the change in groundwater quality. This study also proposes the major tasks for the next few years to control and manage groundwater exploitation to alleviate environmental problems.

Land subsidence is one of the most severe geo-environmental problems induced by excessive groundwater abstraction in China. **Ma et al.** present the general status of land subsidence in three typical affected areas of China and review some typical changes in the water–rock interactions in subsided areas. They point out that the subsidence development and distribution are controlled by the groundwater-withdrawal intensity externally, and by the thickness and compressibility of unconsolidated sediments internally.

3pt?>Among the groundwater quality problems, micro-organic contaminants (MOs) in groundwater are currently gaining increased attention in China. **Dong et al.** summarize the sources, distribution, concentration level and behavior of MOs in groundwater in China. Their study reveals that the majority of MOs in groundwater include PAHs, organochlorine pesticides (OCPs), PBDEs, PAEs, and antibiotics. Some PFCs such as perfluorobutane sulfonic acid (PFBS), perfluorobutanoic acid (PFBA) and perfluorooctanoic acid (PFOA) have only recently been observed in groundwater as emerging organic contaminants (EOCs), and most MOs are detected in densely populated and industrialized areas such as along the southeast coast of China.

Being one of the most important water supply sources, karst water and its quality have always been the focus of hydrogeologic study in China. **Liang et al.** summarize the general characteristics of karst systems in northern China. Five structural models of karst water systems are identified, including the unidirectional incline bedding type system, the unidirectional incline inverse type system, the strata type system, the syncline basin type system, the fault block type, and other types. The environmental problems associated with the karst water systems in northern China over the past 40 years include deterioration of water quality, drying up of springs and continuous decline of karst water level.

China's cold regions with permafrost and seasonal frost provide important water resources. Regional permafrost degradation has been observed in recent decades under impact of global warming and human activities, affecting ecology and water resources; thus, greater understanding of frozen subsurface hydrogeology under the changing environment is urgently needed. **Chang et al.** provide a general overview of the groundwater-related research and issues in the permafrost regions of China, the interplay between permafrost distribution/degradation and groundwater flow regime, and of groundwater and surface-water interactions under impact of global warming. This review hopefully provides a theoretical basis for studying the evolution of cold regions groundwater systems and their ecological environment under the impact of climate.

Anthropogenic geo-environmental problems of groundwater systems

To better manage groundwater use, the interplay between groundwater over-exploitation and its induced geo-environmental problems has been intensively explored. **Su C. et al.** use long-term (1985–2014) monitoring data of isotopic (δ^{18}O, δ^{2}H and ^{14}C) and hydrochemical composition of groundwater to evaluate aquifer responses to intensive exploitation in the North China Plain (NCP), with the aim of obtaining a better understanding of the groundwater sustainability of intensively exploited aquifers. This study notes that enhanced local recharge and irrigation return are observed in the unconfined aquifer, and there are risks of groundwater contamination due to intensive groundwater exploitation. Older groundwater, not involved in the modern hydrological cycle, has been abstracted from the deep aquifers for decades. The current water utilization exceeds the sustainable production capabilities of the aquifer system in the NCP.

The NCP has been a focus of the groundwater studies due to aquifer depletion, but the NCP has also suffered land subsidence for a long period. **Gong et al.** explore the long-term changes (1971–2015) of groundwater storage (GWS) and land subsidence in the NCP and their relationship with in-situ observations and satellite measurements from GRACE and InSAR. GWS exhibits a trend of continuous decline of -17.8 ± 0.1 mm/year, presented in the article as equivalent water height during 1971–2015, a negative correlation to groundwater exploitation rate before the year 2000, and a positive correlation after the year. The temporal distribution of land subsidence differs among three regions (Beijing, Tianjin, and Hebei). The negative correlations between total groundwater abstraction and land subsidence after the 1980s bring into question the reliability of inferring subsidence from regional abstraction data, while a groundwater storage anomaly generally provides a reliable correlation with subsidence.

The Guanzhong Basin is one of the largest basins in China with a semi-arid climate. It features a booming economy and has suffered serious groundwater depletion in the last 30 years. The first **Wang W. et al.** paper notes a clear warming trend and a decreasing trend in rainfall since the 1960s. The combined climate change and intensive human activities have caused a continuous decrease in groundwater recharge and groundwater levels, as well as degradation of groundwater quality and associated changes in the ecosystems, such as localized salinization and an obvious decline of base flow to the river.

As one of the most intensive human activities in China, coal mining has greatly changed groundwater flow and water quality. **Qu et al.** characterize the chemical and isotopic composition of mine waters and groundwater in an underlying limestone aquifer to identify their sources at three abandoned mines in the Fengfeng mining district. The study shows that the mine waters originate mainly from the underlying Ordovician limestone groundwater inflows, and the upward hydraulic gradient in the limestone aquifer may prevent its contamination by the overlying abandoned mine water.

Water diversion projects could significantly affect the groundwater flow regime and surface-water runoff. **Xia et al.** have developed a new distributed surface-water and groundwater coupling model named 'the distributed time variant gain model-groundwater model' (DTVGM-GWM), which considers the interaction between surface water and groundwater at basin scale, to assess the influence of climate change and inter-basin water diversion on the hydrological cycle in Haihe River Basin (HRB) in eastern China. Their modeling results indicate that the DTVGM-GWM can reasonably represent surface and river runoff and spatiotemporal distribution of groundwater level, groundwater storage and phreatic recharge. The possible impact of climate change and the SNWDP on surface water and groundwater are predicted. Prediction results show a decrease in annual groundwater exploitation and runoff in the HRB, with an increase in groundwater storage and groundwater level after the implementation of the SNWDP. The model also projects a slight increase in evapotranspiration, soil water content and phreatic recharge. Using a numerical groundwater flow model, **Zhu et al.** quantitatively evaluate the impact of an inter-basin water transfer project located in the upstream portion of Nalenggele River, the biggest river in the Qaidam basin, northwestern China. The implementation of the project would lead to a 2–5-km downstream movement of the spring emergence sites at the front of the oasis, a 42 million m^3/year reduction in spring discharge, a maximum decrease of 3.6 m in groundwater level at the front of the oasis, and the potential replacement of reeds by *Tamarix*, shrubs and other alternative plant species.

Deterioration of groundwater quality

The unique hydrogeology of karst aquifers makes karst water extremely vulnerable to anthropogenic contamination. **Jiang Y. et al.** explore the environmental effects of the catchment's urban area on the Laolongdong karst groundwater resources in Nanshan, southwestern China. The high-frequency monitoring data of spring discharge, temperature, electrical conductivity (EC) and pH data indicate a coexistence of conduits and narrow fissures in the Laolongdong karst aquifer. The impact of urban pollution is reflected in the hydrogeochemical and microbial data. Groundwater flow could be modified by urbanization, which could increase the magnitude of urban floods in the underground river. Sulfuric and nitric acids introduced by urbanization affect the karst groundwater quality and cause a significant perturbation in the carbon cycling system.

Zhang Zh. et al. investigate the influences of groundwater extraction on the transport and mobilization of arsenic in the Hetao Basin, Inner Mongolia (China). Extensive groundwater extraction caused water level to have two troughs each year in the groundwater irrigation area, and groundwater levels exhibited a decreasing trend from 2011 to 2016; meanwhile, groundwater levels in the river-diverted (Yellow River) water irrigation area had two peaks each year. Total dissolved solids (TDS) and arsenic exhibited an increasing trend from 2011 to 2016. As a result of a reversal in groundwater flow direction, the Shahai Lake acts as a new groundwater recharge source, which increased groundwater salinity by flushing the near-surface sediments. Downward hydraulic gradients were also induced by groundwater exploitation, resulting in leakage of shallow high-TDS groundwater to the deep semiconfined aquifer.

Groundwater salinization is one of the most serious eco-environmental problems induced by human activities in China. Combining the chemical and isotopic tracers, **Li et al.** identify the origin and processes of groundwater salinization in the Daguansha area of Beihai, southern China. Land-based sea farming induced the groundwater salinization in the unconfined aquifer, while the groundwater from the shallowest confined aquifer was contaminated jointly by seawater intrusion and infiltration of seawater from the culture ponds. Water leakage from this contaminated confined aquifer further induces the salinization of groundwater in the underlying confined aquifer.

Geogenic high-fluoride groundwater is widely distributed in China and poses a public health risk. **Liu et al.** investigate distribution and migration mechanisms of fluoride in groundwater in the Manas River Basin, northwestern China. The fluoride concentrations increased with the groundwater residence time and well depths in the northwest of the alluvial-fluvial plain, where groundwater is over-exploited for agricultural and domestic use. The enrichment and migration of fluoride in the groundwater flow system are controlled by geochemical reactions such as cation exchange, and hydrological processes such as vertical leaching by irrigation return flow and mixing with pore water.

Surface-water/groundwater interaction

Groundwater and surface-water interaction play a fundamental role in affecting water resources quantity, water quality and riparian ecosystems. Thus, studying groundwater and surface-water interaction is a crucial issue for better management of water resources.

The second **Wang W. et al.** paper explores the modes and associated hydrodynamic processes as well as ecological impacts of river–groundwater transformation in Junggar Basin, northwestern China. Four typical modes are characterized primarily by geological structure, lithology, flow subsystems, and gaining/losing river status. The local and regional groundwater flow subsystems are suggested to exist at ~400 m depth, forming a multistage nested groundwater flow system. The zonation of groundwater hydrochemical types occur both horizontally and vertically. Surface-water bodies such as streams, wetland and terminal lakes, are the discharge points of the groundwater flow systems. Both groundwater and surface water could be recharged by the same source, and their interaction controls the hydrodynamic and hydro-chemical processes and ecological effects in arid areas.

In arid regions, the groundwater/surface-water interaction is particularly important for sustainable use of groundwater resources. **Lin et al.** investigate groundwater sustainability and groundwater/surface-water interaction in arid Dunhuang Basin, northwestern China, with a groundwater flow model. The change in groundwater/surface-water interaction is also predicted after the completion of a water diversion project. The simulated results indicate that the negative water balance for the current years will be reversed after introduction of water from outside of the basin, and groundwater discharge will change to groundwater recharge after implementation of the water diversion project. The model predicts that the increased net river infiltration due to the water diversion project will raise the water table and, thus, the regional phreatic evaporation will be enhanced, which may intensify soil salinization.

Su X. et al. characterize redox zonation for different groundwater flow paths by interpreting the hydrogeological conditions and water chemistry in groundwater during bank filtration near Liao River, Shenyang, northeastern China. The chemical components varied horizontally and vertically in redox zones during bank filtration. Variations in the horizontal extent of the redox zone are controlled by the depth-dependent permeability of the riverbed sediments and aquifer, and thus by different flow paths. The precipitation and seasonal river floods affect the vertical extent of the redox zone, which extends to 10 m below the ground surface. Arsenic adsorbed onto the surface of aquifer grains or coprecipitated is released into groundwater during bank filtration, due to reductive dissolution of iron and manganese oxides or hydroxides.

Teng et al. investigate hydrogeochemical responses to interaction between surface water and groundwater (SW–GW) along a 10-km-wide area along both sides of the Songhua River, northeastern China. Different modes of SW–GW interactions along the Songhua River are identified, showing that groundwater discharges into the surface water upstream of the study area, surface water recharges the groundwater downstream, and discharge and flow-through processes co-existed in between. The hydrogeochemical response is clear in recharge and flow-through modes, but less obvious in discharge mode. Groundwater contaminants are released by geochemical reactions such as adsorption, redox reactions, nitrification, denitrification, and biodegradation during the water's hydrogeochemical response to the SW–GW interaction in the hyporheic zone.

Gan et al. identify the flow patterns and major processes controlling the hydrogeochemistry of groundwater in the Jianghan Plain, central China. Carbonate and silicate weathering controls major ions such as Ca, Mg and HCO_3 in surface water and groundwater. Iron and arsenic are geogenically derived from redox reactions in shallow confined groundwater. High Cl and SO_4 concentrations in surface water and phreatic groundwater are mainly released due to anthropogenic activities. The different hydrochemistry and controlling processes between phreatic and confined groundwater aquifers suggest that the two aquifers may belong to different groundwater flow systems.

Understanding the contribution of groundwater to Poyang Lake, the largest freshwater lake in China, is crucial for the lake's protection and management due to its ecological and economic importance. **Liao et al.** estimate groundwater discharge and associated chemical fluxes into the Poyang Lake using isotopic data. The results show that groundwater mainly discharges into the lake, with a rate of 24.18 ± 6.85 mm/day and a flux of $(2.24 \pm 0.63) \times 10^7$ m^3/day, accounting for 6.52–11.14% of river-water input in the Poyang Lake area. Groundwater-derived heavy metals such as iron and manganese are potential threats to the lake ecological system.

Groundwater flow

For sustainable management of groundwater resources, it is essential and fundamental to understand groundwater flow. As the third largest desert in China, the groundwater flow in Badain Jaran Desert (BJD) has attracted numerous researchers and has generated debates about controversial hypotheses. Focusing on BJD groundwater, **Wang and Zhou** give an overview on the origin of the groundwater, the hydrological connection between the BJD and the Heihe River Basin, the infiltration recharge, the lake–groundwater interactions, and the features of stable isotope compositions. Their study shows that the significant difference in water levels between the surrounding mountains and lowlands at the western and northern edges drives the groundwater flow at the regional scale. The regional flow promotes discharge of groundwater from BJD to the downstream Heihe River Basin. The quasi-steady groundwater discharge leads to seasonal fluctuations in lake water levels of up to 0.5 m.

The Ordos Basin in northwestern China is one of the most intensively studied groundwater basins in the whole of China. **Jiang X.-W. et al.** explore the pattern of regional groundwater circulation in the Ordos Plateau by combining different approaches. The regional groundwater outflow to other catchments from topographic highs of a catchment is suggested by open water-table contours; while discharge areas in topographic lows are indicated by groundwater-dependent lakes/rivers, topography-driven flowing wells, water-loving and/or salt-tolerant vegetation, and soap holes. Seasonal fluctuations in the water table in discharge areas are caused by variations in groundwater recharge and evapotranspiration and can be used to estimate groundwater inflow and evapotranspiration rates. The local flow systems are superimposed on regional flow systems in the lowest reaches of the basin. To better investigate the impact of production wells at Haolebaoji in the Ordos Basin on the water table, **Nan et al.** apply an adapted algorithm—the random walk on grid method (WOG)—to assess the impact of groundwater exploitation on water head change in the unconfined and confined aquifers. The head values provided by WOG match those derived from numerical flow models. WOG provides information on the contributions of various source/sink terms such as different production wells and boundaries. With this contribution information, head values of interest can be evaluated even by hand when the quantities of these terms change.

To investigate ground evaporation from a homogeneous unsaturated zone, **Zhang Za. et al.** conduct an in-situ experiment in Ordos Plateau of China to investigate evaporation from bare ground with different water-table depths. Air temperature controls evaporation from the bare ground when the capillary fringe of the water-table depth reaches the ground surface. In this case, no zero-flux plane exists in the unsaturated zone, and groundwater contributes to evaporation at the ground surface. Whereas, when water-table depth is much larger than the capillary height, the evaporation amount relies on the water storage in the unsaturated zone, implying that groundwater contributes little to evaporation at the ground surface. Similar results are provided by **Chen et al.**, who also conducted a field experiment to estimate bare soil evaporation for different water-table depths (WTDs) in the wind-blown sand area of the Ordos Basin. This study notes that soil-surface-evaporation rate is dependent on moisture content and air temperature. Only when the WTD is within the capillary fringe does phreatic water contribute to soil-surface evaporation, which indicates that phreatic water would not take part in soil evaporation when the WTD is deeper than the capillary height.

Geothermal resources are competitive clean-energy alternatives to fossil fuels, and their sustainable exploitation could be supported by understanding recharge conditions for the geothermal aquifer system. **Lu et al.** use geochemical and isotopic (δ^2H, δ^{18}O, δ^{34}S, ^{87}Sr/^{86}Sr, δ^{13}C, ^{14}C and ^{3}H) data to trace the recharge and circulation of geothermal water in the Tangshan Geothermal System near Nanjing, China. A local recharge source feeds the system from the exposed Cambrian and Ordovician carbonate rocks area on the upper part of Tangshan Mountain. The reservoir temperature can reach up to 87 °C, which requires a groundwater circulation depth of around 2.5 km. Mixing with shallow cold water lowers the thermal water temperature. A very low circulation rate of thermal groundwater is suggested by ^{14}C age, which promises sufficient residence time for the water to be heated in the system.

Qian et al. study groundwater flow in a karst aquifer of the northeastern Huaibei Plain, China, with major ion geochemistry. A hydrochemical boundary observed at 50 m depth and different geochemical characteristics suggest two flow compartments involved in different hydrological cycles—a local, shallow, rapidly replenished compartment versus a regional, deep flow compartment. Stagnant water flows result in groundwater salinization. Mixing of karst groundwater with pore water is also observed at the later evolutionary stage of groundwater.

Zhou et al. investigate the interlayer staggered zones in the Emeishan Basalt of early Late Permian, located in the Baihetan hydropower project area in Jinsha River Basin, China. They propose a hydrogeological structural plane division method involving interlayer staggered zones for basalt, the fillings of the structural plane, and the particle size and permeability of surrounding rocks. The permeability of each section of an interlayer staggered zone varies within a certain range at small scales, while it tends to converge to a similar value as the scale increases.

Hao Q. et al. optimize groundwater artificial recharge systems using a genetic algorithm in an alluvial fan in Beijing, China. An optimization model directly incorporates the groundwater flow model, to maximize the recharge water volume into the aquifers while meeting hydraulic constraints. A parallel genetic algorithm, with a multiplicative penalty method and relative fitness scaling function, is proposed to solve this optimization problem. The optimization scheme improves the efficiency of the recharge system by increasing the recharged water amount into the aquifers under different scenarios without exceeding the upper limits of groundwater levels.

Conclusions

The articles collected in this thematic issue describe different aspects of groundwater flow systems in China under the impact of fast-economic development, considering groundwater flow, groundwater quality, groundwater and surface-water interaction, and geo- and eco-environmental problems related to groundwater exploitation. It is clear that theoretical and technological innovation is urgently needed to guarantee sustainable exploitation of groundwater resources. The balance of meeting the need for groundwater and refraining from causing ecohydrological and environmental problems should be maintained by improving groundwater knowledge and management. Thus, studying and ensuring the sustainability of groundwater resources has become a top priority for the community of hydrogeologists in China, while in addition, optimized and integrated use of surface and groundwater is fundamental for a sustainable water supply. China's nationwide groundwater-monitoring network needs to be improved to monitor the evolution of groundwater systems.

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