Groundwater in Arid Regions of China

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Abstract: Groundwater is an immensely important and dependable source of water in arid regions including both urban and rural areas of developed and developing countries. The ecological environment in arid regions is extremely fragile and excessive development of groundwater resources may cause lots of ecological problems, and even ecological crisis in some areas. Maintaining sustainable development of socio-economy under the conditions of protecting and rehabilitating the ecological environment pose a great challenge for groundwater research in the arid regions. The paper summarizes key points mostly studied by international researchers, then gives a brief introduction to groundwater researches in arid regions of northwestern China, and introduced several key research aspects with emphasis on conjunctive surface water-groundwater use and management, social ecology and groundwater, groundwater salinity, variability of aquifer parameters, groundwater management, monitoring techniques, groundwater system under the impact of climate change. Key issues are put forward to improve the eco-environmental problems in arid regions of China including the relationship between groundwater and groundwater dependent ecosystems, developing the integrated Oasis-hydrosphere-economy models, strengthening the National Groundwater Monitoring Network, using the new techniques such as environmental isotope, remote sensing and groundwater geophysics. The final solutions of water-related problems in northwestern China will be from many engineering and non-engineering projects, such as shifting steadfastly the inappropriate pattern of economic growth, carrying out energetically restructuring of industry ingand building high-efficiency, water-conservation and pollution-control economy and society.

Key words: Arid regions, ecological rehabilitation, surface water-groundwater interaction and water cycle, groundwater monitoring and management, oasis-hydrosphere-economy models.

Arid and semi-arid areas account for about one-third of the earth's land area and are inhabited by approximately 20% of the total world population. Due to low precipitation and high potential evapotranspiration water resources in arid regions are scarce. Therefore, the economics and living standard of the people are mostly poor. With the rapid socio-economic development in recent decades, the increasing water deficits result in many conflicts which influence resources, environment, ecology and development, and are often complex and inter-related. In arid regions, groundwater plays an important role in the water supply for rural, domestic, industrial, agricultural and ecological water use. Especially during the drought seasons, groundwater becomes a more reliable resource. High exploitation of groundwater may cause serious ecological problems like desertification and soil salinity.

The arid regions in northwestern China include the Xinjiang Autonomous Region, Hexi Corridor of Gansu Province, western part of Helan Mountain of Ningxia Autonomous Region and much of the western part of Inner Mongolia (Fig. 1). Here the increasing population and the high land development activities without efficient water use are putting immense pressure on the available water resources. Considering the groundwater and its relation with surface water and land resources in the arid regions, decision-making and optimization in water management is a difficult task that encompasses many engineering, social, and economic constraints and objectives. For keeping balance between the water uses for different purposes in arid inland areas, Chinese government has taken steps to rationally allocate water resources for different development and management programmes. The present paper provides an introduction to groundwater in arid
inland regions of northwestern China, and some key research contents.

**Groundwater in Arid Region of China**

**Groundwater survey and exploration**

The use of groundwater in China has a long history, dating back to at least 5700 years (Zhang, 1997). With the assistance of USSR hydrogeologists, hydrogeology was introduced as a subject in some colleges in 1952, from where Chinese scholars learned about groundwater movement and management. From the 1950s to the early 1960s, regional hydrogeological survey and mapping at 1:500,000 and 1:200,000 scales were carried out in northwestern China. Between the 1960s and 1970s, China was under rapid development, which increased the demand of water for urban, industrial and mine construction. In northwestern arid regions, many wells were drilled and many researches focused on exploration of groundwater. This gradually led to many environmental problems, such as the disappearing of springs.

From the mid-1980s (the 7th and 8th Five Year Programs for Science and Technology Development in China), groundwater assessment and its rational utilization in northwestern China began (Bureau of Geology Science & Mineral and Resources in Gansu of China, 1984). Since the late 1980, use of many new techniques including groundwater numerical models, hydro-chemical analysis, environmental isotope and GIS, RS, started for sustainable development of groundwater (Wang, 2003). Presently, more attention is focused on the water-related ecology protection in arid regions, and many projects are devoted to save the degraded environment.

**Groundwater cycle**

In the arid inland basin, groundwater distribution pattern varies with the broad regional slope from mountainous areas and alluvial fan of Gobi zone to the oasis and desert areas. Surface water and groundwater are transformed several times during the whole hydrological cycling process. The groundwater system in Hexi corridor
is typical of the arid region of China, and is commonly divided into two sub-basins, called the North sub-basin and the South sub-basin. Groundwater is relatively rich in the alluvial plain and floodplain, where it is recharged by rivers in the upper desert plain areas and discharged by springs and evapotranspiration in lower plain areas.

By using system theory approaches, groundwater system circulation and evolution model in inland basin of North-west of China are discussed. Li et al. (1995; 1999) illustrated the basic principle for the division of groundwater system and explained the different water quality features in the upper and lower aquifers in typical basins of Northwest China. Pan et al. (2004) also put forward the division and identification of groundwater system to depict water cycle pattern in both horizontal distribution and vertical section. The approaches are based on comprehensive analysis of aquifer medium, hydraulic field and geochemistry characteristics to reveal the rules of groundwater flow and salt migration in the basin.

Groundwater quality, salinity and water pollution

Groundwater quality is characterized by regional zoning controlled by the geomorphology, topography and aquifer media. Three zones could be divided surrounding the basin, i.e. fresh water zone in upper alluvial fan area, slightly mineralized overflow zone and salt concentration zone. Groundwater quality in the lower part of the watershed has usually high total dissolved solids (TDS), especially in shallow groundwater.

Salinity affects agriculture through reducing crop yields and increased farm production costs, due to the need for additional leaching and drainage systems. Long-term salinity of groundwater in arid regions may cause soil degradation. Groundwater flow is intricately linked to salinity transport (Bauer et al., 2006). Salinization is a major problem that results from excessive irrigation of agricultural lands.

In the Minqin Basin of the Shiyang River Basin, the salinized area increased from $1.73 \times 10^4$ ha in the 1950s to $2.53 \times 10^4$ ha in the year 1995, constituting 64% of the cultivated area. The cultivated area in Xinjiang is $3.15 \times 10^6$ ha, including more than 1/3 with salinization of various degrees. The area recently brought under cultivation and abandoned due to salinization is $6.67-10.00 \times 10^5$ ha. In some regions the area of cultivation is approximately equal to the area of abandonment, resulting in enormous economic losses (Chen, 1995). Groundwater is generally distributed on low plains, where the water table is shallow and well irrigation is appropriate. If well irrigation is predominant and combined with well drainage as well as with canal irrigation then soil salinization may no longer be inevitable, and a water resources could be economized.

Groundwater pollution is also a new problem in Northwest area. Dong et al. (2006) reported that about 30% of collective groundwater source supply was slightly polluted in plain areas of Northwest region in year 2000. It needs attention for salt water intrusion problem in some areas where fresh water may suffer the pollution by salt water in nearby aquifers caused by over-pumping.

Ma (2001) proposed the IRRUDQELTS indexes comprising of ice melt-water ratio to runoff, groundwater recharge ratio and runoff infiltration ratio to groundwater, runoff use ratio, groundwater pumping ratio, evapotranspiration and its discharge, groundwater quality, water level fall-down and spring water reduction to assess the groundwater vulnerability in the south edge of Tarim Basin where the ecology is fragile.

Three typical river basins: Problems related to water resources development

The Heihe River Basin: The Heihe River is the second largest inland river, with a total length of 821 km. The river originates from a glacier in the Qilian Mountains, at the northeast edge of the Tibetan plateau, then flows north-east across the Zhangye Basin in Gansu Province before ending in the Ejina Banner of the Inner Mongolia Autonomous Region. The middle reaches of the river basin is a commodity grain production base with developed irrigation farming. The Heihe River Basin has experienced rapid socio-economic development and an increase in population density. The Ejina oasis, which is located at the downstream, is irrigated by the river, which blocks the influx of wind and sand from Mongolia. Climatic change and excessive abstraction over the past 30 years have caused surface runoff to decrease sharply in the river's lower reaches, which has resulted in the disappearance of large areas of wetland vegetation, including rose willow, poplar, and other plant species, and has led to worsening
desertification and the intensification of sandstorms in the area (Hui et al., 2005).

In 1995, the total water resources in the Heihe River Basin amounted to $4.202 \times 10^9$ m$^3$, of which surface runoff accounted for 89.9% and groundwater for 10.1%. The total runoff at the Liuyuanbu station, located in the upper-middle reaches of the Heihe river, was $2.37 \times 10^9$ m$^3$, but only 66.7 and 18.3%, respectively, of this water reached the Yingluo gorge and Langxingsa stations. These stations are situated in the lower-middle reach and at the entrance to the lower reaches. Shallow groundwater resources, estimated at $1.443 \times 10^9$ m$^3$ are also a very important part of the region's water (Feng et al., 2001). It is estimated that less than half of the groundwater resources will be exploitable in the future, as these have been overexploited, in a clearly non-sustainable way, beyond the systems' renewal ability.

The Tarim River Basin: The Tarim River Basin is located in the Xinjiang Uigher Autonomous Region (XUAR) in far Western China and is the largest internal drainage basin in China, with a total area of about 1 million km$^2$ with total annual surface runoff of 30 billion cubic meters. The Tarim River is a typical inland river in arid area without runoff yield of itself, and water resources are supplied by its headstreams (Song et al., 2000; Lei et al., 2001). The basin includes returning water to the river for ecological purposes and better managing of land and water salinity. The Tarim Basin is an important part of the XAUR’s economic development. Irrigation is extensive with about 1.5 million ha of irrigated land using 15 Bm$^3$ of surface water and 0.3 Bm$^3$ of groundwater annually. The basin produces one sixth of China’s cotton as well as grains and fruit. Serious eco-environmental problems have developed over the last 40-50 years. For example, until recently, the lower 300 km of the Tarim River had not received water for 20 years and this seriously degraded the natural ‘green corridor’. Shallow water tables and soil salinity are also endemic in the irrigated areas and surface drains are widely used to drain shallow water table. The quality of drainage effluent is often of 8-10 g L$^{-1}$ and as a result has a major impact on river water quality.

The Shiyang River Basin: The Shiyang River Basin (SRB) is located in the Hexi Corridor of Gansu Province, China. It is a typical inland arid basin with a high utilization of water resources. The SRB covers an area of approximately 41,000 km$^2$. The SRB is surrounded by the Badain Jaran Desert in the north, the Tengger Desert in the east, the Qilian Mountain in the south, and the Heihe River Basin in the west. The annual precipitation is 300-600 mm, while the potential evaporation reaches 700-1200 mm. The annual river runoff, mainly in the mountainous area, is $15.75 \times 10^9$ m$^3$. The SRB consists of four sub-basins, which are the Wuwei sub-basin (WWB), the Minqin sub-basin (MQB), the Yongchang sub-basin (YCB) and the Jinchuan sub-basin (JCB) (Wang, 1995). The WWB and the YCB are part of the upstream basin, while the MQB and the JCB are part of the downstream basin. Two important reservoirs lie between the upstream and downstream, which are the Jinchuanxia Reservoir (JCXR) between the YCB and the JCB, and the Hongyashan Reservoir (HYSR) between the WWB and the MQB. Each sub-basin has relatively independent groundwater flow system. Under intense human activities, springs in the middle part of upstream basin decreased rapidly, from $3.0 \times 10^5$ m$^3$/a in 1990 to $0.5 \times 10^5$ m$^3$/a in the year 2000. Currently, groundwater depth in the MQB is in the range of 5-30 m. In the arid region, water use in the upstream will affect the mode of water use in the downstream, and so conflict in water resources use and allocation between the upstream and downstream has been in existence in the basin since the early Qing Dynasty. Due to continuous groundwater overexploitation, the ecological and hydrogeological environment such as soil desertification has been degraded.

Groundwater Investigation and Monitoring in Arid Regions

General methods for groundwater monitoring

Groundwater monitoring well is a kind of basic sources of knowing the change of groundwater system. In groundwater monitoring applications, some of the important factors that play a role in deciding suitability of monitoring network designs include contaminant types, regulatory requirements, extent of plume spread in the aquifer, hydrogeological conditions of the site, proximity to potential exposed receptors (e.g., drinking water wells), surface water interactions, post-remediation effects, social constraints, legal constraints, political constraints, etc. The geology structure is often very complex. To understand this complexity, geologists have a limited number of clues or well data, whose interpretation requires several assumptions and may lead to alternative solutions. For groundwater monitoring programs, these objectives are attained
by managing the network density and the sampling frequency (Zhou, 1996). Various site-specific issues can introduce different qualitative criteria that are crucial for establishing a successful program. These programs can provide useful feedback in analyzing overall acceptability of monitoring plans. It is the requirement that developing a methodology for optimal observation network design for parameter structure identification is to minimize experimental cost, subject to data sufficiency requirement (Chang et al., 2005).

Environmental isotopic application in groundwater

Every kind of water has the distinct isotope composition because of the isotopic fractionation in the transfer and circulation among precipitation, surface water, groundwater, water in soil and plant. Therefore, environmental isotopic, as the label of origin of water, is applied in groundwater investigation including recharging and dating of groundwater, the estimation of the elevation of recharge area, the sources composition of runoff, the interaction between surface water and groundwater, as well as the leakage between aquifers. Both stable isotopes and radioisotopes are utilized in groundwater investigation, the former mainly in the analysis of groundwater sources and cycling approaches, while the later mainly in the dating and tracing of groundwater. Chen et al. (2006) discussed the recharge and origin of groundwater and its residence time in Heihe River Basin by using environmental isotopic measurements. The δ¹⁸O and δD values of both river water and groundwater were within the same ranges as those found in the alluvial fan zone, and lay slightly above the local meteoric water line. This indicates that mountain rivers substantially and rapidly contribute to the water resources in the southern and northern sub-basins. Tritium results in groundwater samples from the unconfined aquifers gave evidence for ongoing recharge, with mean residence times of less than 36 years in the alluvial fan zone, about 12-16 years in agricultural areas, and about 26 years in the Ejina oasis. In contrast, groundwater in the confined aquifers had C¹⁴ ages between 0 and 10 ka BP. Li et al. (2006) discussed the regional environmental isotopic characteristics of groundwater and their hydrogeological interpretation in the Tarim Basin.

Remote sensing application

Early researchers used airborne thermal infrared data and synthetic aperture radar imagery to monitor groundwater (Whiting, 1976; Dobrynin et al., 1998). Rodell et al. (2002) utilized GRACE (Gravity Recovery And Climate Experiment) data to monitor groundwater storage changes for long term in high plains aquifer in central US. Maaleen (2007) presented the groundwater monitoring techniques using both GRACE and ERS satellite images in continental or global scale. Supha et al. (2004) proposed a method for estimating spatial variation of subsurface water level change caused by crop growth from Landsat TM images, by simply using Normalized Difference Vegetation Index (NDVI) relationship with groundwater level in an irrigation project in Thailand. Tashpolat et al. (2005) discussed the use of thermal infrared data of Landsat TM to groundwater level estimation in the oasis-desert ecotone in an arid area of Northwest China. For long-term groundwater monitoring, special considerations should be given to a higher temporal resolution of remote sensors with an appropriate spatial resolution.

Groundwater numerical modeling

The numerical groundwater simulation model is a very effective tool for groundwater investigation, evaluation and management. Wu et al. (2003) established the groundwater simulation model for Ejina sub-basin of Shiyang River Basin, and evaluated the effectiveness of surface water allocation scheme to groundwater recovery. Pan et al. (2004) developed a numerical simulation model for groundwater flow, by using MODFLOW with the aid of Geographical Information System (GIS) and remote sensing technique, to predict the groundwater dynamic under the future condition of land and water resources development and utilization in Shule River Basin.

Groundwater Development and Management in Arid Regions of China

Social ecology and groundwater

Oases are unique humanistic-natural landscapes in arid zones. Landscape patterns are often directly affected by the depth to groundwater (Shi et al., 2000). Extreme spatial and temporal distribution of the depth to groundwater within ecosystems in arid regions can place severe constraints on the ability of trees to meet transpiration requirements during key periods of the growing season. The relationship between the ecology and groundwater requires far more attention for the optimum growth of plants. The long-term reliability of groundwater may encourage riparian trees to
develop roots predominantly in the capillary fringe and saturated zone rather than throughout the soil profile, especially if precipitation during the growing season is unreliable (Ehleringer and Dawson, 1992). Field experiments have proven that many tree species in water-limited environments depend on groundwater (Xia et al., 2001; Cui et al., 2005; Lubczynski, 2009). Lubczynski also discusses the current understanding of the hydrogeological role of trees in water-limited environments, the partitioning of tree transpiration into groundwater and unsaturated zone contributions and the integration of that partitioning in numerical groundwater models. Also unsaturated soil layers by riparian vegetation may depend on the interaction between site conditions and species assemblage (Snyder and Williams, 2000).

Due to the scarcity of water resources, the correct evaluation of water losses by the crops as evapotranspiration (ET) is very important in these regions (Abdalla, 2008). The most common ET measurement methods are: hydrological, micrometeorological and plant physiological, remote sensing (Rana and Katerji, 2000; Goodrich et al., 2000). Evaporation from bare soils results in a considerable loss of moisture and has a direct impact on crop yield in rain-fed agriculture of arid and semi-arid regions. Under annual field crops the soil surface remains bare for many weeks when the moisture content of the upper soil layer can be of critical importance during periods of seed germination and seedling establishment as well as during the subsequent growth of the young crop (Mellouli et al., 2000). Li et al. (2007) used GIS and the landscape structure analysis program FRAGSTATS to calculate and analyze landscape metrics in Minqin Oasis based on TM images from 1987 to 2001. Jin et al. (2009) developed a methodology for the quantitative assessment of eco-environmental changes at a large scale in arid regions by integrating remote sensing methods in ecohydrological approaches and accurately measured evapotranspiration at the Heihe River Basin.

**Groundwater system under climate change**

Global warming due to greenhouse effect is expected to cause major changes in climate of some areas. The change in climate is likely to have a profound effect on hydrological cycle such as precipitation, evapotranspiration and soil moisture. Evapotranspiration, being the major component of hydrological cycle, will affect crop water requirement and future planning and management of water resources (Goyal, 2004). Xu et al. (2004) investigated the plausible association between climate change and the variability of water resources in the Tarim River Basin. They found although precipitation and the streamflow from the headwater of the Tarim River exhibited significant increase, decreasing trend was detected in the streamflow along the mainstream of the river. It implies that anthropogenic activities instead of the climate change dominated the streamflow cessation and the drying-up of the river.

**Conjunctive surface water-groundwater use and management**

Interactions between groundwater and surface water in arid regions play a fundamental role in keeping ecosystems and optimal use of surface water and groundwater for the economic development. Understanding the exchange of water, material and energy between surface water and groundwater components of the hydrologic cycle is critical to effectively address water quality and supply problems as well as to maintain ecosystem diversity and functioning (Winter et al., 1995; Sophocleous, 2002). The interactions between surface water and groundwater are regarded as a research hotspot for a long time.

Many researches in China are concerned with this issue. From the experimental view, the conversion of water among atmosphere, surface water, soil water and groundwater in arid regions was analyzed by Shen et al. (1992). Lei et al. (2001) used the water consumption model to study the conversion among surface water, soil water and groundwater in the Tarim River Basin. Cui et al. (2001) summarized the conversion of the two systems by the field observation data. Lan et al. (2002) also studied the characteristics of surface water-groundwater interaction in the Hexi inland arid regions. Song et al. (2006) used the environmental isotope to judge the conversion of surface water and groundwater in Huaisha River Basin. Wu et al. (2003) and Hu et al. (2007) simulated the interaction among rivers, springs and groundwater in the Heihe River Basin by using the numerical groundwater flow model. A coupled model, integrating rule-based lumped surface water model and distributed three-dimensional groundwater flow model, was established to investigate surface water and groundwater management scenarios that may be designed to
restore the deteriorated ecological environment of the downstream portion of the Shiyang River Basin (Hu et al., 2009).

To sum up, there are three main methods for studying the surface water-groundwater interaction. The first basic method is to record observations and make hydrological analysis, such as field experiment, and long term analysis of runoff of surface water (Shen, 1992; Lan, 2002; Wang, et al., 2004; Newman et al., 2006). Another important method is environmental isotopes along with geology, hydrochemistry and in situ physicochemical parameters (Kumar et al., 2008; Lamonstagne et al., 2005; Song et al., 2006). The most popularly used method is the numerical model for qualifying the flux exchange and mass transfer between surface water and groundwater (Werner et al., 2006; Velazquez et al., 2008). With the occurrence of popularly software such as InHM (Abel et al., 2008), MODHMS (Panday and Huyakom, 2004), MIKE SHE (Refsgaard, 1997), Hydrogeosphere (Therrien et al., 2007), models are widely used in the management of surface water-groundwater resources in the arid regions.

Groundwater management

It has now come to be widely recognized that groundwater governance is not the exclusive forte of hydrogeologists (Mukherji and Shah, 2005). In understanding the challenge of sustainable groundwater management anywhere in the world, it is critical to blend groundwater resource, user communities and institutional perspective. Improving water use efficiency of irrigation systems may also reduce negative environmental impacts. Lining canal systems reduces conveyance losses in surface waterbased irrigation systems. For example, lining of 80% of an extensive canal system in the Shiyang River Basin (Gansu Province) increased the water efficiency of the canal system from 0.30 in the 1950s to 0.54-0.72 in 2000; however, groundwater recharge was reduced by 53% resulting in 15 m groundwater level declines in the past 40 years (Kang et al., 2004). These groundwater level declines have resulted in die-off of sand fixation and windbreak vegetation, resulting in desertification.

The management of groundwater resources is still weak, with more burdens in terms of groundwater resources protection. Over the years, simply relying on the management by administrative departments alone, but not on the role of markets that can play an important part in water reallocation, has not yielded desired results (Sun, 2005). The economic means such as water price is not adequate in terms of water resources protection. Chen (2005) that integrating a rational irrigation system, including channels, streams, springs and water wells to adopt different approaches in different zones, and then to strictly control the groundwater level in an optimal condition.

Ecosystem Remediation Projects for three typical basins

The projects to use the Tarim River and Heihe River Basins have been implemented, and the project on Shiyang River Basin has made a good start since 2007 (Table 1). Water transfer and treatment project in Heihe Basin are carried out from the year of 2000, which has revived the Juynhai Lake and fish has appeared. The area of E'jina oasis is now enlarged. The Chinese government and the World Bank have also implemented a program of integrated river basin management in the Tarim River Basin.

The Water Conservancy and Hydroelectric Investigation and Design Institute of Gansu has made extensive investigation and negotiations within each state and district, with a view to improving the ecological and hydrogeological environment in the downstream of the Shiyang River Basin (SRB), and has developed the framework for water allocation in the basin including development of water-saving agriculture, defining economic structures, controlling groundwater exploitation and diverting water from other rivers. The comprehensive water resources planning in the SRB was approved by the Chinese government in 2007. The effectiveness of ecosystem remediation for SRB is still under review.

Prospect and Future Research

Groundwater dependent ecosystems

Groundwater dependent ecosystems (GDE) are a diverse and important component of biological diversity. The term GDE takes into account ecosystems that use groundwater as part of survival, and can potentially include wetlands, vegetation, mound springs, river base flows, cave ecosystems, playa lakes and saline discharges, springs, mangroves, river pools, billabongs and hanging swamps (Hatton and Evans, 1998). Many documents are related to the relation between groundwater and vegetable (Kang et al., 2007). In arid regions, the topics such as baseflow
Table 1. Water Resources Allocation and Watershed Ecosystem Remediation for three typical basins during recent years

<table>
<thead>
<tr>
<th>Issues</th>
<th>Tarim Basin</th>
<th>Heihe River Basin</th>
<th>Shiyang River Basin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Problems</td>
<td>Downstream river is drying up, serious degeneration of oasis.</td>
<td>The river-end lake dried up, regional groundwater level declining, the oasis degeneration.</td>
<td>Regional groundwater level declining, the oasis degeneration and land desertification.</td>
</tr>
<tr>
<td>Causes</td>
<td>Water resources over-development in upstream and middle stream.</td>
<td>Water resources over-development in the middle stream for agriculture.</td>
<td>Regional groundwater level decreasing because of the decreased runoff to downstream and over-pumping of groundwater for irrigation.</td>
</tr>
<tr>
<td>Remediation measures</td>
<td>9 times water delivering to downstream from year 2000, of which 6 times water reached Taitema Lake. The total water volume to downstream is about 2.26 billion cubic meters during 9 years.</td>
<td>Total water volume to downstream, E’jina Basin, reached 4.6 billion cubic meters during 8 years. About 0.3 billion cubic meters water entered the East Juyan Lake.</td>
<td>To increase the runoff to downstream by water saving measures, to reduce the irrigation area in the downstream region. The purpose is to increase the regional groundwater level. The measures are just under implementation. Under review.</td>
</tr>
<tr>
<td>Effectiveness of ecosystem remediation</td>
<td>The groundwater level is increasing, while the oasis is of recovery.</td>
<td>Larger surface water in the river-end lake maintained since 2005. The oasis in E’jina extended about 40 km².</td>
<td></td>
</tr>
<tr>
<td>Researchers or reporters</td>
<td>Tursun et al., 2008; Xu et al., 2008; Chai et al., 2008; Wan et al., 2008.</td>
<td>Ning, baoying, He et al., 2008; Xi et al., 2008; Wei Zhi et al., 2007.</td>
<td>Hu, 2007; Zhang et al., 2007; Wang et al., 2003.</td>
</tr>
</tbody>
</table>

component and ecology-groundwater relation are key issues.

**Environmental isotope, remote sensing and groundwater geophysics**

Environmental isotope has been demonstrated as a good method for detecting the sources of groundwater, and for better understanding of the behavior of groundwater movement. This method has been applied to many arid regions of northwestern China (Chen et al., 2004) and will continue to serve as an important method. Remote sensing is also applied to analyze the change of landuse and evaporation (Edmunds et al., 2006). Groundwater geophysics provides a potential method for obtaining the information on geology structure. Standard geophysical exploration techniques will not provide direct information on the permeability structure of the probed medium, and so it requires making further research on the connection between probed data and the permeability structure (China Geological Survey, 2004).

**Development of integrated Oasis-hydrosphere-economy models**

The improvement of eco-environment not only depends on the research on groundwater itself, but also on the economy and surface water management. Integrated Oasis-hydrosphere-economy models can reflect the real situation in arid regions of northwestern China, including the coupled surface water-groundwater use, economy constrains, human activities and the influences of climate change. Cold and Arid Regions Environmental and Engineering Research Institute in China (Cheng et al., 2008) has taken almost five years to build an integrated model for the Heihe River Basin and may develop another successful model in the future. National Science Foundation Committee of China has established a major research plan for Heihe Basin, named Heihe...
Basin Ecological and Hydrological Processes Integrations.

**Digital basin and information technique**

Water is an essential factor for the social and economic development. To meet the increasing demand of water improved watershed management is required. This necessitates the development of integrated management tools, which utilize spatially-distributed coupled models, spatially-distributed data as well as local and regional knowledge. While each component might be available to decision-makers, the necessary integration of spatially-distributed models of watershed, data and knowledge through GIS is still in its infancy.

**Conclusions**

The northwest arid region of China occupies about 27.3% of the total area of China and the influence of human beings here is far less broad than the Eastern Monsoon Region. Its ecological environment is extremely fragile. Through more than two thousand years of territorial reclamation, particularly through more than fifty years of rapid economic development after the founding of New China, excessive development of water and land resources has occurred in many localities, resulting in many ecological problems, and even some ecological crisis. Maintaining sustainable development of socio-economy under the conditions of protecting and rehabilitating the ecological environment will therefore pose great challenge for the northwestern region.

Three possible key research thrusts in the future are put forward to improve the eco-environmental problems in arid regions: studying groundwater and groundwater dependent ecosystems; using the new techniques, including environmental isotope, remote sensing and groundwater geophysics; developing an integrated oasis-hydrosphere economy model. The final solutions of water-related problems in northwestern China will be from engineering and non-engineering projects, such as shifting steadfastly the inappropriate pattern of economic growth, carrying out energetically restructuring of industry and build high-efficiency, water-conservation and pollution-control economy and society.

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