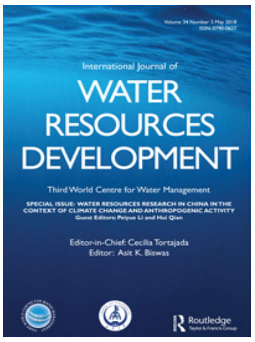

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Challenges and prospects of sustainable groundwater management in an agricultural plain along the Silk Road Economic Belt, north-west China

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ABSTRACT
As a major challenge in building a new and sustainable Silk Road Economic Belt, threats induced by poor groundwater management have raised stress on the groundwater resources in the Yinchuan Plain, north-west China. In the present article, an overview of groundwater development in the plain, along with the associated negative effects, is provided. A fragmented management framework is found responsible for the poor groundwater management. Efficient and effective groundwater management will require proper attention of the local authorities to the inherent interaction among various water systems. Only with enhanced cooperation, an integrated monitoring network, strengthened scientific support and active public participation can the sustainability of groundwater management of the plain be achieved.

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Groundwater; deterioration; sustainability; Yinchuan Plain; arid area; Silk Road

Introduction

Groundwater represents one of the largest stocks of accessible freshwater and accounts for about one-third of freshwater consumption globally (Famiglietti, 2014; Gorelick & Zheng, 2015). Owing to its relatively stable yield of high-quality water, groundwater has emerged as an extremely important water resource for meeting domestic, industrial, agricultural and environmental demands (Howard, 2015). Although groundwater is often relatively well protected from pollution, poor management has resulted in negative impacts such as declining aquifer heads, groundwater quality deterioration, lower crop yields, ecosystem degradation, and in some cases, land subsidence and seawater intrusion (Praveena, Abdullah, Bidin, & Aris, 2012; Schoups, Addams, Minjares, & Gorelick, 2006; Wagner, 1995). With rapid industrialization and with intensification of agriculture, groundwater sustainability has become a major concern for China (Cao, Zheng, Scanlon, Liu, & Li, 2013; Ministry of the Environment, 2013). The situation is more serious in the arid and semi-arid areas, which lack perennial sources of surface water. Indeed, groundwater is the main, if not the only, water source to support domestic water supply and economic prosperity in arid areas such as the Yinchuan Plain.

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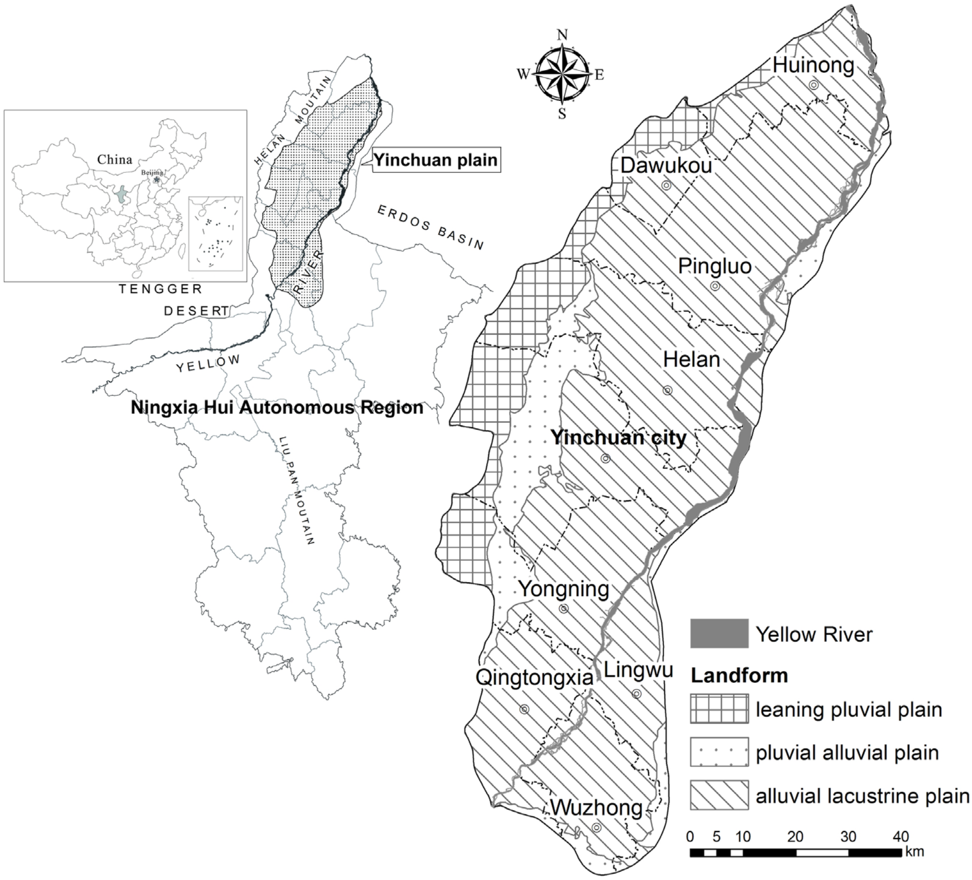

Figure 1. A map showing the location of the Yinchuan Plain and its landforms.
Source: Zone boundary from Chen & Qian (2015).

The Yinchuan Plain is a historical agricultural area along the Silk Road Economic Belt in north-west China, covering an area of 6704.5 km^2 (Figure 1). This region is the lowest expanse of Ningxia, with elevations of 1100–1200 m above mean sea level. The Yinchuan Plain is home to approximately 46% of the total population of Ningxia (about 3 million), and most of the industrial parks of Ningxia are located in this area. This alluvial plain of the Yellow River has been irrigated for more than 2000 years and is one of the national centres of wheat and rice production owing to its fertile soils. While the annual precipitation is 190 mm, the annual evaporation is 1850 mm (approximately 10 times as much). This is possible because groundwater is utilized intensively. Actually, groundwater has given rise to abundant social and economic benefits in the region because of its minimal infrastructure requirements, ease of access, fairly uniform yield and high water quality. Both urban and rural populations in the plain rely entirely on groundwater for their daily domestic needs. Groundwater is used in all kinds of industries, and it also serves as a reliable source of irrigation supply to ensure crop production during times of drought and shortage of surface water supplies (Table 1).

In September 2013, Chinese President Xi Jinping delivered a landmark address at Nazarbayev University in Astana, Kazakhstan, in which he reaffirmed China's commitment

Table 1. Different uses of groundwater in the Yinchuan Plain in 2008 (10^4 m^3).

City	Irrigation	Industrial	Domestic supply	Rural supply and livestock	Total
Yinchuan	800	6,347	6,813	353	14,313
Yongning	83	1,360	329	287	2,059
Helan	467	1,233	569	241	2,510
Lingwu	244	1,473	402	354	2,473
Dawukou	590	3,205	941	38	4,774
Pingluo	444	1,797	180	349	2,770
Huinong	796	1,818	780	121	3,515
Litong	50	1,833	702	585	3,170
Qingtongxia	274	2,304	367	371	3,316

Source: Ningxia Water Resources Department (2009).

to promoting world economic growth and international collaboration through creation of a new Silk Road Economic Belt that will connect the country with its neighbours to the west, including Central Asia, the Middle East and Europe (online news at http://news.xinhuanet.com/english/china/2013-09/07/c_132700695.htm). Such a large-scale project would bring profound economic prosperity to the entire region. However, much of the belt area in north-west China and Central Asia is in semi-arid and arid regions, where the natural environment is highly vulnerable and groundwater is a vital resource for various purposes (Li, Qian, Howard, & Wu, 2015; Libert, Orolbaev, & Steklov, 2008). Ensuring the development of the new Silk Road in a sustainable way implies that the management of the groundwater resource should be given considerable attention. For the Yinchuan Plain, intense competition for groundwater among agricultural, industrial and domestic needs has raised stress on the precious resource. The consequences have been reported as depletion in groundwater level, deterioration of water quality, soil salinization and ecological damage (see e.g. Chen, Wu, Qian, & Liu, 2015; Chen & Qian, 2015; Li, Qian, & Wu, 2014; Li, Wu, & Qian, 2016; Qian, Li, Howard, Yang, & Zhang, 2012a; Wu, Li, Qian, & Fang, 2014; Wu & Sun, 2015). In this context, development of the area as a part of the new and sustainable Silk Road Economic Belt means a further increase in industrial and agricultural activities, which will put even more pressure on groundwater supplies (Li et al., 2015). The problems are likely to be aggravated by climate change and the ever-increasing global population (Kundzewicz, Mata, Arnell, et al., 2007; Vaux, 2011). Despite the importance of groundwater, an overview of groundwater development and a strategy for effectively managing the groundwater in the Yinchuan Plain are still unclear. This situation raises a question about whether the groundwater resources in the plain can sustainably support the various uses on a long-term basis.

The purpose of this article is to understand the issues associated with groundwater development on a regional scale, and to suggest possible approaches for the sustainable management and regulation of this precious resource for the plain. This article gives an overview of the negative effects of groundwater development. The problems and challenges to groundwater management specific to the Yinchuan Plain are discussed. To provide useful guidelines for decision makers, recommendations are made for achieving sustainability.

Groundwater conditions in the Yinchuan Plain

Hydrogeological setting

The Yinchuan Plain is inclined from south-west to north-east. Geographically, the landforms are the leaning pluvial plain, pluvial alluvial plain and alluvial lacustrine plain, respectively,

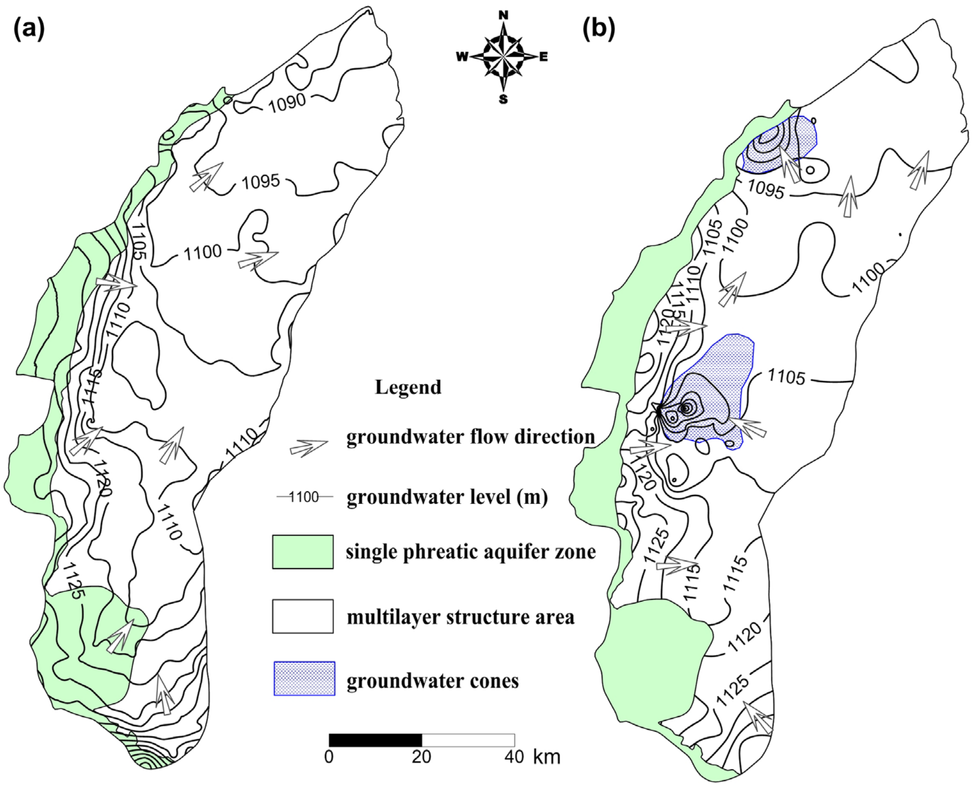

Figure 2. Groundwater contour maps as of June 2003: (a) phreatic water; (b) confined water.
Source: Modified from Qian et al. (2012a).

from west to east, as shown in Figure 1. The pore water in the loose rock mass forms a huge underground reservoir. As shown in Figure 2, two aquifer systems exist in this plain within a depth of 250 m:

(1) A single phreatic aquifer zone that is primarily composed of mountainous pluvial deposits, and alluvial sand and gravel of the Yellow River.
(2) A multilayer structure area comprising a phreatic aquifer and upper and lower confined aquifers (from the top down), mainly covered by lacustrine and alluvial deposits. The phreatic aquifer and the upper and lower aquifers are separated by aquitards, which are normally continuous and have thicknesses in the range of 3–10 m.

Overall, groundwater in the plain flows in the NNE direction (Figure 2). In most areas of the plain, the depth of the water table is less than 3 m. The aquifers of the Yinchuan Plain are recharged mainly by irrigation channels, irrigation infiltration, precipitation, inflow through lateral boundaries and infiltration of floodwater during storm events (Qian et al., 2012a). A regional estimate shows that more than 80% of the total inflow of the groundwater comes from (a) leakage from irrigation channels, and (b) seepage of irrigation water applied to fields (Table 1). Outflow of the groundwater occurs primarily as (a) discharge to drains and to the Yellow River, (b) evaporation, and (c) artificial extraction. Evaporation is very

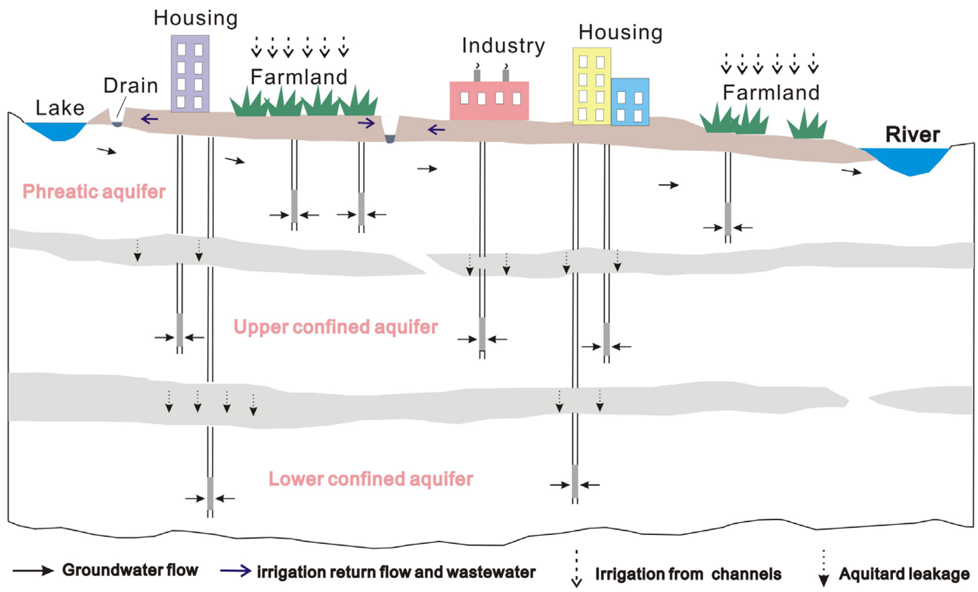

Figure 3. Schematic view of the hydrogeological system in the plain.

Table 2. Groundwater balance in the Yinchuan Plain (from Qian et al., 2012a).

Inflow	Percentage of total	Outflow	Percentage of total
Water leakage from channels	59.45%	Evaporation	46.59%
Irrigation infiltration	22.69%	Discharge from drains	21.72%
Precipitation	6.54%	Discharge to Yellow River	4.27%
Boundary inflow	9.86%	Artificial extraction	27.44%
Flood recharge	1.46%		
Total amount	22.21×10^8 m^3/y	Total amount	21.28×10^8 m^3/y

Source: Qian et al. (2012a).

intense in the plain, accounting for about 47% of the total outflow (Table 2). A schematic diagram of the hydrogeological system of the Yinchuan Plain is presented in Figure 3. Interdependence is observed among the various water systems, including precipitation, groundwater, Yellow River and lakes, and this interaction has indeed been the driving factor underpinning socio-economic development and maintaining the ecological balance of the plain (Qian, Li, Wu, & Zhou, 2012b; Wang, Hu, Yin, Wan, & Yu, 2012).

Groundwater use

As shown in Figure 4, the consumption of groundwater in the plain shows a clearly increasing trend. The annual consumption of groundwater increased from 1.5×10^8 m^3 in 1970 to 4.8×10^8 m^3 in 2012. The markedly increased groundwater consumption in 2003 is mainly attributed to the reduction in the amount of surface water available for irrigation plants. After that, a control system was adopted, and a large number of self-supply industrial wells were phased out. The control system has been effective in keeping the groundwater pumping rate relatively stable.

The groundwater in the confined aquifers and in the single phreatic aquifer is preferred for potable and industrial supplies due to its good water quality. Census data show that the

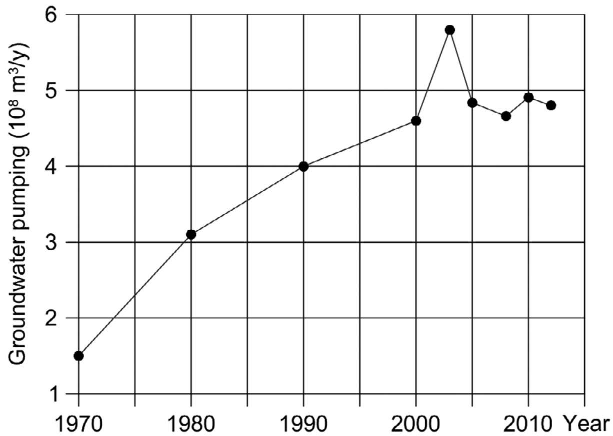

Figure 4. Consumption of groundwater in the Yinchuan Plain, 1970–2012.
Source: Data from Wu, Qian, Yu, Zhang, & Yan (2008) and Ningxia Water Resources Department (2013).

urban population of Ningxia Hui Autonomous Region increased from 1.8 million in 2000 to 3.3 million in 2012 (Ningxia Statistical Bureau, 2013), and greater rates of urban population growth are still expected in this plain. Rapidly expanding cities require increasing amounts of groundwater for potable supply. Similarly, approximately 54% of the pumped groundwater (21.4 million m^3/y) is currently used for industrial water. For instance, Shizuishan City (including Dawukou, Huinong and Pingluo) is an old industrial city in the plain that is largely dependent on groundwater to support its economic growth. The industrial sector contributes approximately 66.8% of the total GDP in the city, and over 50% of the industrial water demand relies on groundwater. Therefore, groundwater is depleting at an unprecedented rate due to the ever-increasing demands for public water supply and industrial use. As shown in Figure 2(b), two drawdown cones have been noticed in the confined aquifers, in Yinchuan and Dawukou, respectively. The depletion of groundwater due to persistent pumping started to attract policy makers' attention in the early 1990s.

Rural communities are also completely dependent on groundwater for domestic water supply. Groundwater is generally extracted from individual shallow tube wells with depths of less than 30 m. Field investigation indicates that water from such tube wells is consumed untreated by the majority of the rural population. The villagers are of the opinion that the groundwater is safe and clean. This is mainly due to inadequate scientific knowledge on human health effects.

Furthermore, in the whole region, groundwater irrigation supports a fairly stable water supply for ensuring good crop yield. It provides 3.7 million m^3 of water for irrigation per year. Because of the easy accessibility for users, there are more than 2300 wells in the plain for irrigation alone. Many farms in the irrigated areas, however, use groundwater only when not enough water is delivered to grow sensitive crops, particularly during drought periods.

Problems of groundwater development

Groundwater depletion

Groundwater depletion is an inevitable and natural consequence of withdrawing water from an aquifer. Excessive depletion is indicated by a persistent and substantial head drop

Table 3. Degree of exploitation of groundwater in Yinchuan Plain.

Cities	Current exploitation (10^8 m^3/a)	Usable amount (10^8 m^3/a)	Exploitation potential coefficient	Over-exploitation degree
Yinchuan	1.43	2.44	1.70	low
Yongning	0.21	2.36	11.45	low
Helan	0.25	2.38	9.48	low
Lingwu	0.25	1.79	7.24	low
Dawukou	0.48	0.14	0.30	Over-exploited
Pingluo	0.28	3.45	12.44	low
Huinong	0.35	2.37	6.73	low
Litong	0.32	1.32	4.16	low
Qingtongxia	0.33	1.25	3.76	low

Source: Data from Wu et al. (2008).

resulting from the pumping of groundwater at a rate higher than replenishment. The scale of the problem has been quantified globally (Konikow & Kendy, 2005). The Yinchuan Plain, without exception, is suffering from groundwater depletion, and the two groundwater depression cones are getting deeper and wider (Figure 2). A survey by the Land Resources and Monitoring Institution of Ningxia indicated that the areas of influence of the cones in Yinchuan and Dawukou had reached approximately 440 km^2 and 61 km^2, respectively, in 2012. The drawdowns of water levels at the centres of the aquifers were greater than 10 m. Although the cones have been in a stable condition in recent decades, preventing further decline in groundwater levels remains an ongoing concern.

The degree of exploitation is an important parameter and influences the impacts of groundwater pumping (Shi et al., 2007). In this article, the degree of exploitation is calculated by the groundwater exploitation potential coefficient method recommended by the China Geological Survey (2004). The coefficient is defined as the ratio of the usable amount of groundwater to its current exploitation amount. When the value is less than 0.6, it denotes a seriously over-exploited status. The range of 0.6–0.8 indicates over-exploited status, while 0.8–1.2 indicates recharge balance status. Values exceeding 1.2 represent low exploitation status. As shown in Table 3, coefficients greater than 1.2 were found in the majority of the cities and counties, indicating a large groundwater exploitation potential. Therefore, for Yinchuan City, despite the presence of a groundwater depletion cone, there is still a large groundwater exploitation potential. Since water supply wells are primarily located in and around the cone, the effect of pumping is concentrated in the vicinity of the cone and causes depletion that appears inconsistent with the groundwater explanation potential. On the other hand, in Dawukou (the second cone), the coefficient indicates over-exploited status. Combined with the persistent and substantial head depletion in the cone, the large demand for groundwater is a serious issue in the city, which is a groundwater prospective area and which has substantial economic gains closely associated with industry.

Quality deterioration

Groundwater's quality is as important as its quantity. It has been well documented in the literature that shallow groundwater is relatively more vulnerable to contaminants underneath agricultural areas with well-drained conditions. Due to the thin and permeable unsaturated zone, the shallow aquifer (< 40 m) is at a great risk from anthropogenic activities (Qian & Li, 2011). Given the intensified anthropogenic activities, a variety of chemicals, including nitrate, ammonium, and heavy metal elements (such as Cr, Ni, Pb and Zn), can easily pass through the soil and potentially contaminate groundwater (Li & Qian, 2011; Qian et al., 2012a). Among the many contaminants of groundwater, nitrate is particularly common in agricultural areas due to high-N fertilizers and poor irrigation practices. Chen, Wu, and Qian (2016) found that groundwater with high nitrate concentration could have adverse effects on human health through ingestion. Other chemical elements that are controlled by hydrogeological conditions also affect groundwater quality. The enrichment of fluoride (F) and arsenic (As) in groundwater is primarily due to weathering of F-rich and As-rich minerals and water–rock interactions. Han et al. (2013) found that As concentration ranged from less than 1 μg/L to more than 177 μg/L in the shallow groundwater. Field investigation also indicated higher F levels, in the range of 1–1.62 mg/L, in groundwater (Wu, Li, & Qian, 2015). It should be noted that the maximumn concentrations of As and F in drinking water per WHO (2011) guidelines are 10 μg/L and 1.5 mg/L, respectively. High levels of F may cause dental and skeletal fluorosis, and high levels of As may increase the risk of bladder, liver and lung cancer. This implies a large health hazard for residents, especially in rural communities which rely on untreated groundwater for drinking.

Some causes and impacts of groundwater depletion are not easy to assess, such as water quality deterioration (Konikow & Kendy, 2005). For the study area, groundwater depletion was considered not only as a reduction in the volume of water but also as a serious threat to water quality. According to recent studies (Chen et al., 2015; Qian et al., 2012b; Wu et al., 2015), groundwater pumped from confined aquifers has actually induced leakage from the overlying aquifers, causing variation in the hydro-chemical concentrations and isotope compositions in the two cones. Groundwater pumping accelerates the downward migration of pollutants from the ground surface through aquifer leakage. Under such conditions, groundwater with poor water quality and contamination can easily leak into confined aquifers and then contaminate the confined aquifers. As the groundwater depletion continues, the water quality is further worsened.

Environmental degradation

The ecological environment in arid regions is extremely fragile. Improper development of groundwater resources may cause ecological problems, and even an ecological crisis. In the Yinchuan Plain, groundwater has played a key role in sustaining the environment because the eco-environment is very sensitive to the changes in the groundwater levels of the plain. Negative effects have been induced by both high and low groundwater levels.

The Yinchuan Plain is a heavily salinized zone owing to high groundwater tables caused by over-irrigation, canal seepage and intense evapotranspiration (Xiong, Xiong, & Wang, 1996). Relatively higher groundwater salinity and soil salinity were found in the northern part of the Yinchuan Plain, which could be explained in part by the relatively flatter topography and in part by the slower hydrological cycle in the north. According to a soil survey in Ningxia (Wu et al., 2008), the salinized area (soil salinity in the range of 1–10 g/kg) in the Helan, Dawukou, Huinong and Pingluo areas has reached 1730 km^2. Soil fertility could be severely reduced because of the accumulation of soluble salts of sodium, magnesium and calcium in the soil (Tóth, Montanarella, & Rusco, 2008). Intensive irrigation causes secondary salinization in arid areas and makes it difficult and costly to treat salinized areas (Ashraf, Athar, Harris, & Kwon, 2008; Banin & Fish, 1995; Harti et al., 2016; Jensen, Rangeley, & Dieleman, 1990; Stigter, Carvalho-Dill, Ribeiro, & Reis, 2006).

Groundwater is also important in balancing water in lakes and preventing them from drying up (Zhang et al., 2011). Lower water tables can reduce groundwater discharge to springs, streams and wetlands. For example, Shahu Lake is the largest lake in the plain, and groundwater exchange is an essential part of the lake's water budget. Water evaporated from the open-water surface constitutes the major loss from the hydrologic budget of lakes. For Shahu Lake, evaporation from the surface accounts for approximately 92% of the total inflow. In this scenario, the rise of surface water and groundwater demand has caused stress on the available resource for sustaining the lake level and the ecological environment. Since declining groundwater level may adversely affect the hydraulic connectivity between the lake and the groundwater (Chen & Qian, 2015), there is growing concern to ensure replenishment of lake water demand, especially in dry seasons.

Problems and challenges related to groundwater management

Groundwater management in China has evolved from a highly fragmented process in the past to become an institutionally integrated and decentralized process (Foster et al., 2004). Before 1979, tube wells were operated by village leaders. Then, private ownership and management gradually predominated. Groundwater resources are primarily overseen by different agencies at the national level. For this plain, three departments primarily have mandates over the groundwater resource: Water Resources, Environmental Protection, and Land and Resources.

In general, the Department of Water Resources is engaged with investigation and documentation of water quantity and quality, water resource protection and water saving, and agricultural water conservation. The Department of Land and Resources focuses on hydrogeological investigation, environmental assessment, and monitoring water table depletion and groundwater quality. The Department of Environmental Protection oversees pollution prevention, water sources and environmental protection. Under this scenario of divided responsibilities, the absence of a full-fledged groundwater management system has been the main reason for poor management in this plain. Although extensive data and multiple approaches are being used to handle the complex responsibilities, overlapping and conflicting work is inevitable. Differences in governing regimes and frameworks among the departments add to the complexity. Due to the fragmented management framework, water management communities are not keeping pace with what is necessary to resolve the systemic long-term effects of depletion and degradation of groundwater resources. Thus, managing groundwater in a new and innovative way remains an enormous long-term task for the Yinchuan Plain.

Unmanaged use of groundwater is indeed a global problem, caused by the cumulative impacts of increasing population, urbanization, increase in water use with prosperity, changes in land use, inexpensive drilling and pumping technology, industrialization, intensification of irrigated agriculture, stringent water quality standards and climate variability (Immerzeel, van Beek, & Bierkens, 2010). In addition to these general factors, the hydrological cycle of the Yinchuan Plain can be severely affected by changes in water supply from the Yellow River, which is a major contributor to the aquifer system of the plain. Given a clear need for the sustainable development of the new Silk Road Economic Belt, all these factors highlight the urgent need for sustainable groundwater management in the Yinchuan Plain.

Recommendations for sustainable groundwater management

Sustainable management of groundwater is not only about balancing the available aquifer storage to satisfy users' demand, but also about sustaining its quality and environmental diversity in an efficient and equitable manner (Vaux, 2011). In recognition of this fact, a series of national policies and strategies have been promulgated to improve groundwater sustainability. The New Environmental Protection Law of China came into effect in January 2015 (Standing Committee of the National People's Congress of the PRC, 2014). Several national guidelines have evolved regarding environmental impacts, groundwater assessment and agricultural water management, imposing significantly greater controls and responsibilities on corporations and local government bodies. Regions will no longer be judged solely on economic progress, but instead on balanced progress with environment and natural resources. An Action Plan for Prevention and Treatment of Water Pollution was implemented in April 2015 with the aims of improving the quality of drinking water and promoting water saving (State Council of the People's Republic of China, 2015). Detailed guidelines and specific concerns are included in the plan for the protection and prevention of surface water and groundwater. The state government will invest approximately five trillion yuan in water protection under this plan. These legal instruments and proactive measures are important steps to promote the best practices and in-depth studies in advancing the development and utilization of groundwater within the plain. As per the plan, institutions for effective and efficient management of groundwater should be developed and managed locally. Despite the direct involvement of the state government, the plan directs that the local groundwater management institutions should follow the micro-level knowledge of the properties of the aquifer and should solve the root cause of the problem. To change the current situation in the study area, close cooperation among the different departments, careful planning, adequate scientific research, and the support of the public are highly recommended.

Enhancing cooperation

The most important aspect of sustainable groundwater management is to change the fragmented management situation for the Yinchuan Plain. Enhanced cooperation among different departments and adoption of related multilateral arrangements have been recognized as necessary steps to ensure effective protection of groundwater. Actions to realize the benefits of integrated management not only unify groundwater management at a regional scale, but also drive a benefit-sharing mechanism. Thus, groundwater management can no longer be considered in isolation from other departments. Effective implementation of monitoring and management strategies can be realized through a comprehensive and coherent overview of hydrodynamic variation on a regional scale, including information on aquifer condition, groundwater quality, depth of water table, water extraction and pollution sources. Such an approach is expected to support further protecting the rivers, lakes and groundwater sources in this plain. Despite several efforts, it may still be quite challenging to realize integrated cooperation, which is affected by multiple factors such as decision makers and management systems and processes. It may be valuable to share information with other departments at an early stage of any groundwater-related developments.

Integrating monitoring network

Unlike surface water, natural and anthropogenic impacts on groundwater systems are not clearly visible and often occur after a significant delay. Damages to groundwater resources are generally characterized by long-term consequences. To better understand the complexities and uncertainties associated with groundwater resources, monitoring can provide valuable data which are useful for describing, examining and documenting changes in aquifers (Mogheir, Singh, & de Lima, 2006). However, the Yinchuan Plain suffers from the 'data-rich and information-poor' syndrome. Information on variations in groundwater quantity and quality is mostly scattered, and information on critical parameters (e.g. heavy metals and organic matters) is even missing. Insufficient data are available to scientists and stakeholders to ensure that resources are efficiently used and the environment is well protected.

Under these conditions, there is an urgent need to develop and improve an integrated network for monitoring the physical parameters (e.g. temperature and water levels) and the chemical composition of groundwater and surface water bodies (lakes, rivers and drains). Monitoring units for wells and for surface water bodies in different departments should be integrated to provide synthesized information for groundwater management. Contaminants in drinking water, such as nitrate, fluoride, arsenic and heavy metals, should be focused on in the groundwater management procedure. Ensuring the safety of drinking water for rural communities is as important as for urban populations. Importantly, greater concern should be paid to the variation in chemical elements in confined aquifers, and strict supervision should be provided for groundwater pumping, especially around the two water cones.

To ensure accuracy of outputs and simplicity for decision makers, Ningxia has proposed an early-warning system (EWS). The effectiveness of an EWS largely depends on reliable data and long-term tracking of meteorological and hydrogeological data. Since groundwater is a dynamic system, the EWS needs to be updated to reflect the changes in the groundwater system. The EWS can be used to determine sustainable abstraction volumes, feasibility of development and strategy for efficient groundwater management. However, available data on the variations in water level and water quality in the surface water–soil–groundwater system are the major determinants for the success of the EWS. This implies that all available data should be stored and integrated in a database information system on a continuous basis. Efficiency of the data management system is dependent on the efficiency of storing and sharing as well as of managing.

Strengthening scientific support

The ultimate objective of groundwater management is to ensure acceptable quantity and quality of water for health, livelihood and production. Modern management paradigms have essentially three components: water resources; ecosystem; and water security. For the Yinchuan Plain, research alone cannot serve the purpose of management very well, even though many studies have been performed towards groundwater sustainability. Bridging the gap between theory and practice imposes constraints on groundwater management. Accordingly, the interactions among various water bodies are not well understood. Furthermore, due to the limited knowledge of groundwater, it is challenging to implement advanced technologies on the aspects of water saving, groundwater pumping, information collection and simulation of contamination transport.

Under these conditions, scientific research should be directed to better explain, communicate and educate water managers and decision makers (Li, 2016). Science can contribute to the resolution of conflicts, such as those between groundwater development and preservation perspectives, by facilitating a clear understanding of the hydrological processes, by assessing the effects of anthropogenic activities on the quality and quantity of groundwater, by elucidating the role of groundwater in the eco-environment, and by providing a holistic perspective for decision making. Certainly, sustainable groundwater management depends on expertise from outside and universities, but also the support of inside professionals. Modern technologies and modelling tools should be introduced and applied to identify the spatial and temporal distribution and the migration of contamination in the aquifer system, especially in the protected areas for drinking water, landfills, industrial parks and mine lands. Concerned departments should provide more opportunities for professionals to enhance technical knowledge through regular education and training.

Encouraging public participation

Public participation plays an active role in planning and implementation of groundwater management programmes. However, the rights of citizens to obtain groundwater information and to participate in groundwater governance in China have not truly materialized (Zhang & Cao, 2015). Despite the intensive use of groundwater in the Yinchuan Plain, this resource remains inadequately understood by the public. The information on groundwater protection and preservation released to the public is limited, and thus there is no efficient approach to raise public awareness of the need for groundwater protection. Efforts should be made to encourage public participation, which is helpful to supervise industrial and agricultural activities, as well as to improve water savings in urban and rural areas in relation to water-saving technologies, such as spray and drop irrigation. Transparency of information should be maintained for easy access to information and data relevant to the use of and access to water in aquifers, usually through a web service, or a newsletter. Furthermore, better understanding among the public should be brought to implement water-saving practices and pollution-prevention strategies in urban and rural areas. It is important to efficiently implement operational strategy and regulatory mechanisms in practice.

Conclusions

In the Yinchuan Plain, groundwater is a vital resource for domestic, agricultural and industrial supplies, and to support socio-economic development. The existing fragmented groundwater management practice has largely hampered sustainable groundwater development and utilization, by causing negative effects such as groundwater level depletion, water quality deterioration and environmental degradation in the aquifer system. In the work towards building a new and sustainable Silk Road Economic Belt, the intense competition for water resources among agricultural, industrial and domestic users is expected to lead to a sharp increase in stress on the groundwater resource. As such, sustainability of groundwater can be realized only by solving groundwater problems, which are closely linked with the safety of drinking water and the socio-economic development in the plain. The currently promulgated New Environmental Protection Law of China and the Action Plan for Prevention and Treatment of Water Pollution provide great opportunities for groundwater resource management, research and activities. To be effective, the groundwater management institutions should build capacity to face future challenges. In order to achieve sustainable groundwater management, this study has proposed recommendations which focused on empowering the capacity building of the local management offices as well as close interaction among the authorities overseeing various water systems (e.g. precipitation, groundwater, Yellow River and lakes). Finally, sustainable groundwater development for the plain can be achieved through: (1) enhancement of cooperation among different departments; (2) development of an integrated monitoring network to monitor, assess and manage the groundwater resource; (3) in-depth understanding of the scientific knowledge; (4) improvement of technical expertise of professionals; and (5) enhancement of public awareness and participation.

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