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Development of Managed Aquifer Recharge in China

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ABSTRACT

China has a long history in managed aquifer recharge (MAR). The historic development can be divided into 4 stages based on a summary of typical MAR projects. The first stage is MAR applied to agricultural production, the second is MAR applied to industrial production and alleviation of agricultural problems, the third is MAR applied to ecological protection and the increase in urban water supplies, and the fourth is multi-source MAR. In addition, geothermal reinjection and ground source heat pumps are also effective uses of MAR. Nevertheless, the MAR framework is defective, there is a lack of water quality studies, and the recharge rate of most projects is low. However, China has achieved a great effect on industrial and agricultural production, ecological protection, drinking water supplies and urban reclaimed water reuse, amongst others. But there are still many issues to be improved. A feasible, convenient and economic technique of MAR which fits local hydrogeological conditions needs to be developed and guidelines for both MARs and management regulations to ensure the successful running of MAR projects also need to be established. MAR will make a great difference to improving potable water quality, alleviating geological hazards, long distance water diversion, urban water supplies, agriculture irrigation, etc.

Key words: groundwater, GSHP, MAR, water production, water supply.

Desarrollo de la recarga artificial de acuíferos en China

RESUMEN

China tiene una larga historia en la recarga de acuíferos (MAR), que se puede dividir en 4 etapas. La primera etapa comprende la aplicación de la técnica MAR en la producción agrícola; la segunda, en la producción industrial; la tercera en la protección ecológica y para aumentar el suministro urbano de agua, y la cuarta tiene un propósito múltiple. Además, la reinyección geotérmica es también una de las aplicaciones de la recarga artificial en China. Sin embargo, la planificación es defectuosa, el estudio de la calidad del agua es deficiente y la tasa de recarga en la mayoría de los proyectos es baja. Se puede concluir que China ha logrado obtener rendimientos aceptables en los casos de aplicación a la producción industrial y agrícola, la protección ecológica, el abastecimiento de agua potable urbano y la reutilización de aguas residuales. Sin embargo, todavía hay muchos otros campos de utilización posibles. Se sugiere desarrollar una metodología factible, conveniente y económica para aplicar correctamente las técnicas MAR a las condiciones hidrogeológicas locales, y establecer pautas y reglamentos de gestión conjunta para asegurarse de que los proyectos funcionen con éxito. La puesta en marcha de más proyectos de recarga artificial puede suponer una mejora de la calidad del agua potable, una herramienta más en la lucha contra las amenazas o riesgos geológicos, la transferencia de agua a largas distancias, la mejora de la garantía en el abastecimiento urbano o el riego para la agricultura, etc.

Palabras clave: Agua subterránea, GSHP, MAR, recarga artificial, producción de agua, suministro de agua.

VERSIÓN ABREVIADA EN CASTELLANO

Introducción

En China, el consumo de agua per cápita es de sólo 1/4 del promedio mundial. En el norte de China existe una grave escasez de agua y por ello, se han desarrollado problemas de sobreexplotación de acuíferos, que ha originado problemas ambientales , como la subsidencia, la intrusión de agua de mar y el deterioro de la calidad del agua. Las técnicas MAR se consideran como una herramienta eficaz para la gestión integrada de los recursos hídricos . Aunque China ha puesto en marcha con éxito muchos proyectos de recarga artificial de acuíferos para diferentes propósitos desde los años 90 del siglo 20, hay una falta de reglamentos técnicos y directrices científicas para la implantación de este tipo de proyectos.

Durante la aplicación de la recarga artificial de acuíferos en China, se pueden diferenciar cuatro fases:

A. Primera etapa. Aplicaciones para la mejora de la producción agrícola

Los chinos comenzaron a explotar las aguas subterráneas ampliamente desde 2000 ~ 1000 aC . En el período de 475 ~ 221 aC, se comenzó a excavar canales para facilitar la infiltración de las aguas superficiales en el suelo. Más adelante, se comenzaron a usar los karez utiliza para interceptar las aguas subterráneas para su uso en agricultura

B. Segunda etapa. Aplicaciones en la industria y para mitigar desastres agrícolas

Los objetivos de los proyectos MAR se orientaron hacia la restauración de la capa freática, el ahorro de energía y la reducción de costes, el control de la subsidencia del terreno y la mejora del suministro de agua de la industria. Ejemplos reseñables son los de la ciudad de Shanghai, donde se llevó a cabo la recarga de acuíferos mediante pozos profundos desde los años sesenta en el siglo 20 para controlar la subsidencia.

C. Tercera Etapa. Aplicaciones en protección ambiental y suministro urbano de agua

D. Cuarta Etapa. Aplicaciones multiobjetivo

Por ejemplo, inyección de agua regenerada en la ciudad de Zhengzhou , provincia de Henan desde 2002, recarga de un acuífero kárstico con agua tratada procedente de tejados de edificios, puesta en marcha por la Universidad de Jinan, en agosto de 2011, y que todavía sigue funcionando, o la reinyección geotérmica.

Problemas

1. Sistema imperfecto de gestión de los proyectos MAR

Es necesario elaborar una serie de criterios técnicos para la evaluación , la construcción, el funcionamiento y la gestión posterior de este tipo de proyectos, que en la actualidad no existe.

2. Pocos estudios sobre la calidad del agua de origen para la recarga

3. Necesidad de inversiones para poner en marcha este tipo de proyectos. Mayor implicación del Gobierno en este tema

4. La tasa de recarga de GSHP es baja

Conclusiones

China ha obtenido éxito en el control de la subsidencia del terreno, el almacenamiento de energía, la utilización de la energía geotérmica , la prevención de la intrusión de agua de mar, la mejora del suministro de agua a las poblaciones, la agricultura de riego y la mitigación de los desastres agrícolas mediante la puesta en marcha de proyectos de recarga artificial de acuíferos. Sin embargo, todavía es necesario desarrollar una metodología factible, conveniente y económica para adaptarse a las condiciones hidrogeológicas locales, establecer pautas y reglamentos para la gestión de este tipo de proyectos, que permitan asegurarse de que los proyectos MAR tengan éxito.

Introduction

Managed aquifer recharge (MAR) is the deliberate recharge of water to aquifers for subsequent recovery or environmental benefit. Generally, MAR is limited by aquifers, topography, land use and recovered water use in site (NRMMC–EPHC–NHMRC 2009). Types of MAR include ASR (aquifer storage and recovery), ASTR (aquifer storage, transfer and recovery), rainwater harvesting, underground dams, etc (Dillon, 2005).

Water used per capita in China is only 1/4 of the world average level. Groundwater is mainly recharged by precipitation, which is distributed unevenly in time and space (China Groundwater Scientific Strategy Research Group, 2009). In North China, groundwater accounts for only 32.3% of the whole country, with serious water shortage and over-exploitation. This has triggered a series of environment problems, such as land subsidence, seawater intrusion and deterioration of water quality. Consequently, MAR is considered to be an effective measure for the integrated management of water resources. Although China has successfully constructed many artificial groundwater recharge projects for different purposes since the 1990s, there is a lack of technical regulations, that is to say, China has no scientific guidelines for the conduction and supervision of MAR projects.

Stages of MAR in China

A. First stage - MAR applied to agricultural production

The Chinese first began to exploit groundwater extensively in 2000 ~ 1000 BC. In the Warring States period (475 ~ 221 BC), channels were dug to facilitate the infiltration of surface water into the ground, improving groundwater quality and saline land. In the Qin and Han Dynasties (221 BC ~ 220 AC) people dug artesian wells to a depth of 10 ~ 200 m (Hydrology and Geology Research Group in Shanghai, 1977). The *Karez* was invented during this period and used to intercept groundwater for agriculture irrigation and residential water consumption. A *Karez* is generally made up of a shaft, an under drain, an open channel and a water-logging dam (Figs. 1 and 2). The *Karez* guaranteed a stable irrigation water support and a low evaporation of groundwater, which was scarcely affected by surface temperature.

Figure 2. The main elements of a *Karez*.
***Figura 2**. Elementos de un careo.*

The ancient farmers of Huantai County in Shandong excavated transverse galleries along the Wuhe River during the Qing Dynasty. The device was made up of the river, a transverse gallery, a shaft and a manual lifting device (Fig. 3). Shafts were usually excavated at a depth of 7~8 m below the surface and the length of the transverse gallery could stretch several kilometers. There was a shaft every 30 m, which was convenient for construction and lifting. Groundwater was recharged by diverting river water during flood seasons. So then, the water table rose quickly. At that time it was a perfect groundwater recharge project with a much higher efficiency of infiltration than any other structure (Yongchun Wei *et al.,* 1979).

B. Second stage - MAR applied to industrial production and alleviation of agricultural disasters

Most established MAR engineering projects in China play a prominent role in restoring water tables, saving energy and reducing costs, controlling land subsidence and augmenting industrial water supplies.

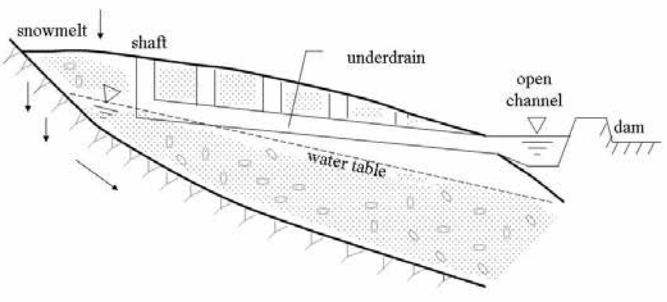

Figure 1. Schematic diagram of a *Karez*.
***Figura 1.** Diagrama esquemático de un careo.*

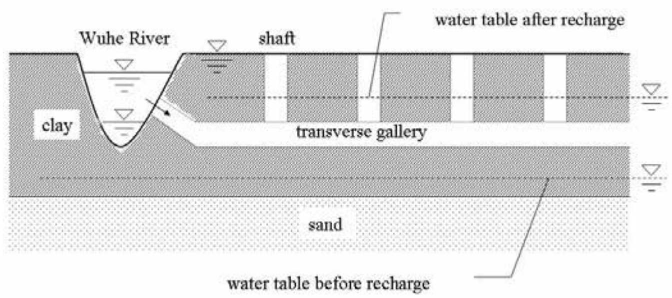

Figure 3. Schematic diagram of a transverse gallery.
***Figura 3**. Diagrama esquemático de una galería transversal.*

For example, Shanghai has conducted groundwater recharge using deep wells since the 1960s to control land subsidence by regulating groundwater exploitation and decreasing water demand. In 1965, five cotton companies in Shanghai carried out injection tests with 4 different water sources. The results showed that injected water had a low velocity and a little variation in temperature. Subsequently, groundwater recharge with tube wells was explored gradually and a design to offer new hot and cold water sources for the factories using the aquifer was developed. Therefore, the water was recharged into an aquifer in the winter and exploited in the summer. By 2000, the total amount of groundwater recharged with tap water had reached 6×10^8 m^3 in Shanghai. The annual average of groundwater recharge was 2×10^7 m^3 and urban land subsidence was effectively controlled (Shiliang Gong, 2006; Yi Liu, 2000). At the same time, this technique of recharging in winter and reusing in summer was applied in Beijing, Tianjin, Xi'an and Nanchang. For example, Beijing conducted groundwater recharge using deep wells in an industrial area from 1981-1999 with a total volume of 1.07×10^8 m^3 (Ying Sun *et al.,* 2001).

In North China, drought, waterlogging and salinization are the most serious natural disasters. The key is to solve the water shortage through diversion using discarded water from the rivers, or transferring extraneous water, depending on local conditions. Wells, ponds, ditches and basins were widely applied in artificial recharge combined with adjusting exploitation volumes, to increase the water resources availability and ensure bumper harvests and stable agricultural production. For example, the irrigation district of Renming Shengli Channel in Henan province carried out a combination of wells and channels: channels for irrigation and wells for groundwater recharge during the dry seasons, in which well water was used instead. In 1975, the irrigated area reached 300,000 hectares and the water table was maintained at 2 m depth, the saline land area decreased and grain yield increased year on year. Another example is in the Wuqiao county of Hebei province a shallow well-deep groove system was applied, carrying out the combination of river, well, swag and channel, as well as using surface and ground water together to realize the comprehensive treatment of drought, waterlogging and salinization. Surface rainfall is generally retained with canal and swag in flood seasons to recharge groundwater, and groundwater is then discharged and retained in river sluices at the end of the flood season. River water is diverted for irrigation in winter. Shallow groundwater is pumped to irrigate farmland with a lowering of the water table and vacating underground capacity in spring. Thus, the level of drought control and waterlogging prevention was improved gradually. However, most aquifer recharge projects were scraped due to a lack of sustainable management. Nevertheless, it is feasible to build intercepting underflow projects in arid regions, in which there is a little surface flow and a relatively higher underflow. It is a practical technology to effectively alleviate the contradiction between water supply and demand and strengthen agricultural drought resistance. For instance, the Alxa League city of Inner Mongolia has built 70 intercepting underflow projects since the 1970s. Amongst them, the largest in Alxa Zuoqi resolved the problem of drinking water for tens of thousands of people with 90 L/s of daily water supply; the latest in Alxa Youqi provided drinking water for 1000 livestock with 0.3 L/s of intercepted flow. Intercepting underflow projects are effective measures to exploit and utilize groundwater from river channels and valley plains in hilly areas (Qinde Sun *et al.,* 2007).

C. Third stage - MAR applied to ecological protection and increasing urban water supplies

In China, costal intrusion areas have reached 1,500 km^2 due to groundwater over-exploitation. Many underground reservoirs have been built since the 1990s, which can transfer excessive flood water to prevent seawater intrusion (shown in Table 1). For example,

Name	Total storage capacity (Million m^3)	Water supply quantity (Million m^3/a)	Area of reservoir (km^2)	Length of underground dam (m)	Average deep (m)
Balisha River in Longkou	0.3	0.5	14	756	8.5
Huangshui River (Longkou)	53.29		51	5842	10
Wanghe River in Laizhou	53.26	23.55	68	14500	10
Shiren River in Qingdao	1.3	1.2	21	620	17

Table 1. Statistical table of underground reservoirs built in coastal areas of China.
Tabla 1. *Relación de embalses subterráneos construidos en China en áreas costeras.*

the Huangshui River underground reservoir, which is made up of 2,518 infiltration wells, 6 sluices and 448 infiltration trenches. The aquifer is recharged by river-bed leakage.

In addition, water consumption has increased sharply with social economic development. What is more, there is a serious water shortage in partial downstream plains. Since 2000, some reservoirs have been turned into integrated ecological designs instead of merely flood control and water supply. For example, the Wohushan reservoir in Jinan City turns on the water in dry seasons to recharge groundwater indirectly with use of channel leakage and to promote spring protection. Another example, in dry seasons, is the water in Taihe reservoir in Zibo City which is discharged to supply downstream groundwater source by infiltration.

D. *Fourth* Stage - multi-source MAR

Different kinds of water resources can be stored using MAR techniques, such as storm water, reclaimed water, tap water or groundwater from other aquifers, after reuse for drinking water supply or agricultural irrigation. For example, the first and biggest urban reclaimed water recharge project in China, the Gaobeidian Groundwater Recharge Pilot Project in Beijing which was completed in 2003 and reached 200 m^3/d of recharge amount under the design condition composed of a surface recharge system and a rapid infiltration shaft system (Guichun Yun *et al.,* 2004). It is shown in Figure 4.

Moreover, the China University of Geosciences has carried out a reclaimed water injection test in the Zhengzhou city of Henan province since 2002. Municipal wastewater is reclaimed using an artificial wetland and the wastewater treatment system and is then conducted to infiltration basins for recharge. The water quality of the outflow from the wastewater treatment system generally satisfies the limit of the water quality standard for groundwater recharge. The recharged groundwater using wastewater reclaimed by the integrative technologies in the Zhengzhou site generally satisfies the criteria for the groundwater quality standard (GB/T14848-1993) and can be used for fishery, industry and agriculture (Menggui Jin *et al.,* 2009). To give another example, a pilot project of a karst aquifer recharge with urban treated roof water was established in the University of Jinan in August, 2011, and still keeps running (shown in Fig.5). Continuous monitoring shows that both the quality of the roof water and groundwater basically met the groundwater quality standard with a recharge amount of 300 m^3 until September, 2012.

Furthermore, geothermal reinjection and ground heat pumps are also an effective utilization of MAR. In early 1982, a geothermal tail water recharge test was conducted in Beijing (Zaisheng Han *et al.,* 2008). Now, geothermal reinjection has become popular on a large scale in Tianjin city. In recent years, the ground source heat pump (GSHP) technique has developed quickly. For example, a kind of GSHP with thermal storage in a deep well could save 20-30 % energy compared to geothermal reinjection, which could also control land subsidence effectively. In 2009, the national technical code for ground-source heat pump systems (GB50366-2005) was issued, which contributed to the development and application of GSHP technology.

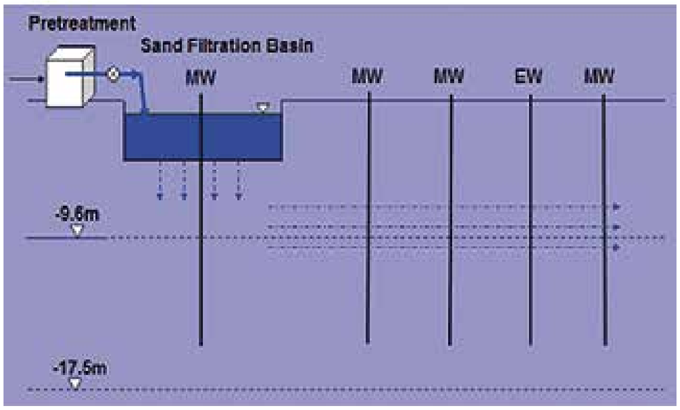

Figure 4. Groundwater Recharge in the Gaobeidian WWTP of Beijing.
Figura 4. Recarga artificial en Gaobeidian, WWTP de Pekín.

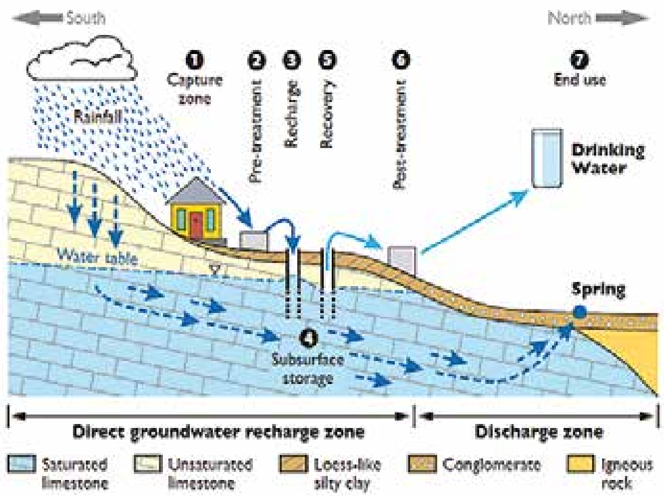

Figure 5. Karst aquifer recharge with urban treated roof water at the University of Jinan.
Figura 5. *Recarga en un acuífero kárstico con agua tratada procedente de tejados en la Universidad de Jinan..*

Problems

(1) Imperfect systems of MAR

Although some rules on MAR were established in China, such as the deep well management regulation in Shanghai (issued in 1963 and revised in 1979) and Interim Regulation for Groundwater Resources Management in Beijing (1981), there is a lack of scientific and complete administrative systems for MAR. Consequently, it is necessary to draft a series of technical criteria for the evaluation, construction, operation and later management etc. for MAR.

(2) Scarce studies on water quality for MAR

In coastal areas, the treated and untreated sewage will make a long-term difference on the water quality of underground reservoirs when upstream pollution control is incomplete. In addition, aquifer recharge with urban reclaimed water still needs further studies. The transfer of studies from water quantity to water quality by monitoring and sampling on site combined with numerical simulation is suggested. Thus, the recharge effect may be quantified.

(3) The investment is inconsistent with the benefits and more attention was paid to construction rather than management

Urban industrial enterprises use MAR to store heat and cool water with a small influence radius of recharge wells and high economic benefits under self-management. In rural areas, MAR has a much higher economical and ecological benefits. The high tide of artificial groundwater recharge emerged before 1978 and rural MAR developed quickly under collective ownership. Later, the household contract responsibility system was implemented in our countryside. Then many recharge projects declined or were even discarded due to a lack of maintenance. Therefore, the artificial groundwater recharge in rural areas came to depend more and more on state investment construction. Groundwater recharge in urban areas has been simply used to recover water tables and increase groundwater resources, and is also has problems of investment and maintenance. Moreover, reservoir administrative departments still have no compensation mechanisms for channel infiltration recharge of groundwater by releasing water. In short, the government should be the investor to offer enough funds for MAR projects.

(4) The recharge rate of GSHP is low

Although there are many applications of GSHPs in China, most projects have still not been able to reach the ratio of recharge to pump water at 100%. The key is to develop groundwater recharge techniques and avoid damage by GSHPs to groundwater resources. Secondly, a further investigation of already constructed GSHPs is needed to discover problems and summarize experiences for sustainable operation.

Finally, the development, problems and solutions of MAR are concluded in Table 2.

Conclusions

China has managed to achieve great advances in land subsidence control, energy storage, geothermal utilization, prevention of seawater intrusion, increases in urban water supplies, agriculture irrigation and alleviation of agricultural disasters using artificial recharge of groundwater projects. However, there are still

Application	Problem	Solution
Agricultural Production	System is imperfect	Draft a series of technical criterion
Industrial Production and Alleviation of Agricultural Disasters	Lack study on water quality	Quantify recharge effect by monitoring and sampling in site combined with numerical simulation
Ecological Protection and Increasing Urban Water Supply	The investor is inconsistent with the beneficiaries and most attentions were paid on construction rather than management	Increase the capital investment
Geothermal Reinjection and Ground Source Heat Pump	Low recharge rate	Develop groundwater recharge technique

Table 2. Development, problems and solutions for MAR in China.
Tabla 2. *Desarrollo, problemas y soluciones de la técnica MAR en China.*

many problems. A feasible, convenient and economic technique of MAR to fit the local hydrogeological conditions needs to be developed. The establishment of guidelines for both MAR and management regulations to ensure MAR projects run successfully is also necessary. In addition, the development of MARs depends on the support of government and investment.

Acknowledgments

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