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Managed aquifer recharge (MAR) applications in China–achievements and challenges

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Abstract: Groundwater is of fundamental significance for human society, especially in semi-arid areas in China. However, due to the fast social and economic development, China has been suffering from the shortage of water resource. In this situation, managed aquifer recharge (MAR) was considered to be an effective measure for the sustainable management of groundwater resources. Since 1960s, China successfully implemented many MAR schemes for different purposes such as restoration of groundwater tables, prevention of seawater intrusion, increasing urban water supplies and controlling land subsidence. From those successful experiences China developed a scientific and applicable system to implement MAR project. However, there were still many challenges in this field, for example, treated waste water had been barely used for recharge. The present review summarized the achievements in MAR applications in China as well as the associated challenges within the past 55 years before the year 2016.

Keywords: Managed aquifer recharge (MAR); Groundwater; Recharge; Aquifer; Storage

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Introduction

China had suffered severely from water shortage. In the northern and eastern parts of the country, water resources were used at a higher rate than the available storage, leading to the situation that water stress was ranked as 'extreme' in four Chinese provinces and municipality: Shangdong, Jiangsu, Hebei provinces and Beijing (Tan et al. 2015). In addition to the unfavourable climate conditions, the area also had the highest population density (19.74% of the total population living in 4.82% of the total area in China) and high percentage of industry (28.4% of the whole industry in China) according to the data from the National Bureau of Statistics of China. In order to alleviate the negative impact from the serious water shortage, managed aquifer recharge (MAR) had been introduced into China.

MAR is to recharge water source into aquifers for subsequent recovery or environmental benefit. An MAR project includes building infrastructure and modifying the landscape to intentionally enhance groundwater recharge (Dillon, 2005). MAR was among the most prospective ways in China to reduce aquifer vulnerability to climate change and hydrological variability. MAR's benefits include storing water for future use, stabilizing or recovering groundwater levels in over-exploited aquifers, reducing evaporation losses, managing saline water intrusion or land subsidence, and enabling reuse of waste or storm water (Clifton et al. 2010).

The use of MAR techniques for the augmentation of groundwater resources had a long history in China dating back thousands of years. For example, during the Qing Dynasty, the inhabitants of Shandong Province constructed the subsurface channel-wells along the Wuhe River and used river water to recharge groundwater for domestic purpose (Wang et al. 2010). Furthermore, since the 1950s, to meet the increasing water demand in urban and rural areas, many efforts had been carried out to implement various MAR projects,

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like the rainwater harvesting system (Wang et al. 2014).

Though many knowledge and successful experiences were achieved in this field, no attempts had been made to summarize and transfer them to other areas in China and neighbouring countries. For this reason, this study presents a comprehensive review on MAR from the published literatures, intending to provide a general project framework for relative institutions, decision makers and communities, which covers broad topics about MAR such as the appropriate places for MAR project, climate conditions, geological situation, security, quality of supply, environmental and social benefits and constraints.

1 Material and methods

According to the local geographic conditions, atmospheric conditions and even the lifestyles, the MAR in this study is divided into the following main approaches (Dillon, 2005):

1) Spreading methods – such as infiltration ponds, soil aquifer treatment, in which overland flows are dispersed to encourage groundwater recharge;

2) Induced bank infiltration – in which groundwater is withdrawn at one location to create or enhance a hydraulic gradient that would lead to increased recharge (e.g. bank filtration, dune filtration);

3) Well, shaft and borehole recharge – in which infrastructures were developed to inject water to an aquifer to recharge it and then either withdraw it at the same or a nearby location (e.g. aquifer storage and recovery);

4) In-channel modifications – such as percolation ponds, sand storage dams, underground dams, leaky dams and recharge releases, in which direct river channel modifications are made to increase recharge;

5) Rainwater harvesting – in which rainfall on hard surfaces (e.g. building roofs, paved car parks) is captured in above or below ground tanks and then allowed to slowly infiltrate into soil.

In this review, a total of 136 cases of MAR projects were collected from published literature in Chinese and English and then grouped for further analysis based on four primary criteria (i.e. general site information, operation, hydrogeological properties and water quality) shown in Table 1. For each primary criteria, more detailed parameters were determined for the MAR project analysis, for example, 12 specific parameters for the criteria of general information and 16 specific parameters for operation. Due to insufficient description of those MAR projects in the relative literatures, some specific parameters were discussed very little and only the general information was provided.

According to Dillon (2005), these Chinese MAR projects were divided into five major types and 15 specific types on the basis of infiltration methods and interception methods (Table 2); and each of the specific type was assigned a label with a certain colour. Fig. 1 shows the distribution of the specific types of MAR in China (Fig. 1).

2 Results

Within the five primary MAR types (Fig. 2), the spreading method was the most applied in China and totally 46 sites were investigated. The well, shaft and borehole recharge method ranked the second with 40 cases. In-channel modification was also widely applied in China and 34 study cases were collected. 11 cases were carried out using the method of rainwater and run-off harvesting. Very few projects were operated using the method of induced bank infiltration and all 5 cases were collected from Beijing.

Regarding the numbers of specific MAR types in China (Fig. 3), nine specific MAR types were identified, in which the infiltration ponds and basins was the most popular method, adopted in 25 sites, which was followed by subsurface dam (21), ASR/ASTR (21), dug well/shaft/pit injection (19), ditch and furrow (18), recharge dam (13), roof-top rainwater harvesting (11) and induced bank infiltration (5). The methods of flooding and reverse drainage were rarely applied in China, with only one case for each was mentioned by Su et al. (2010) and Guan et al. (2015).

From the distribution of specific MAR cases in different provinces and municipalities (Fig. 4), it could be concluded that the 136 MAR cases were mainly distributed in areas with extremely high risk of water resource shortage (Shangdong, Shaanxi, Liaoning, Hebei Provinces, Beijing and Shanghai). 34 projects were implemented in Shangdong Province, among which the most popular methods were infiltration ponds & basins and recharge dam. 28 projects were carried out in Beijing, and the methods of dug well/shaft/pit injection, ditch & furrow and induced bank infiltration were used. In other areas, the methods of ASR/ASTR, infiltration ponds & basins as well as dug well/shaft/pit injection had been widely

Table 1 Analysis criteria of the 136 MAR projects (entry count is the number of projects, followed by the percentage of projects with the specific parameter data)

No.	Field parameter	Entry count/ %
General information		
01	Name of site	136 (100%)
02	City	127 (93.3%)
03	Province	134 (98.5%)
04	Latitude	116 (85.3%)
05	Longitude	116 (85.3%)
06	Size of site	18 (13.2%)
07	Under operation since (year)	104 (76.5%)
08	Institution	17 (12.5%)
09	Specific MAR type	136 (100%)
10	Objective	124 (91.2%)
11	Influent source	133 (97.8%)
12	Final use	109 (80.1%)
Operation		
13	No. of infiltration structures	55 (40.4%)
14	No. if infiltration wells	29 (21.3%)
15	Avg. filter depth (recharge)	16 (11.8%)
16	Scale of catchment area	8 (5.9%)
17	Reservoir area	10 (7.4%)
18	Reservoir/storage capacity	11 (8.1%)
19	Recharge efficiency	4 (3.0%)
20	Avg. injected/infiltrated volume	17 (12.5%)
21	Initial injected/infiltrated volume	2 (1.5%)
22	Total injected/infiltrated volume	7 (5.1%)
23	Avg. infiltration rate	9 (6.6%)
24	No. of monitoring wells	20 (14.7%)
25	No. of recovery wells	9 (6.6%)
26	Avg. filter depth (Extraction)	3 (2.2%)
27	Avg. extracted volume	5 (3.7%)
28	Horizontal aquifer passage	3 (2.2%)
Hydrogeological properties		
29	Hydraulic conductivity of soils	4 (2.9%)
30	Aquifer thickness	9 (6.6%)
31	Aquifer confinement	96 (70.6%)
32	Aquifer type	96 (70.6%)
33	Development of water table	24 (17.6%)
34	Initial ground water level	13 (9.6%)
35	Final ground water level	16 (11.8%)
Water quality		
36	Hydrochemical data	12 (8.8%)

applied.

Regarding the development of MAR projects with time, the 136 MAR cases had been collected since 1960s (Fig. 5); due to the increasing water demand for industry and domestic purposes after 1960, the MAR technologies started to be widely introduced. Between 2000 and 2009, the number of MAR applications reached the peak value of 37 sites. Furthermore, the application of ASR/ASTR, recharge dam and roof rainwater harvesting was

Table 2 Classification of Chinese MAR projects (Dillon, 2005) and relative references

	Main MAR type	Specific MAR type	Collected literatures
Techniques regarding infiltration method	Spreading methods	Infiltration ponds & basins	Huang and Pang (2013), Jin et al. (2012), Li et al. (2011), Pi and Wang (2006), Su et al. (1996), Su et al. (2014), Xu et al. (2012), Yuan (1979), Zhang (2005), Zhang et al. (2013).
		Flooding	Su et al. (2010)
		Ditch & furrow	Ding (1997), Jia and Li (2012), Li (1997), Li (2009), Li et al. (2007), Liu et al. (2006), Liu and Song (1989), Wang and Zhang (1991), Wei et al. (2014), Yan (2009), Yang et al. (2010), Zhang (2005).
		Excess irrigation	
		Reverse drainage methods	Guan et al. (2015)
	Induced bank filtration	Induced bank filtration	Zhang et al. (2013)
	Well, shaft & borehole recharge	ASR/ASTR	Lu et al. (2014), Liu et al. (2006), Liu and Pan (2014), Qu et al. (2012), Su (2012),Wang et al. (2012), Wang and Qu (2011), Yan et al. (2014), Zhang et al. (2011), Zhao et al. (2004).
		Dug well/shaft/pit injection	Bai et al. (2010),Dong (2010),Dong et al. (2011), Fan (2014), Hao (2011), Liu et al. (2006), Li et al. (2012), Liu and Dai (2013), Qu (2014), Wu et al. (2010), Yang et al. (2010), Zhang et al. (2013), Zhang et al. (2015).
Techniques regarding interception methods	In-channel modifications	Recharge dam	Han (2002), Hao (2011), He and Shen (2010), Huang and Pang (2013), Liu et al. (2004), Sun et al. (2006),Wang et al. (1999),Wang et al. (2001), Wang et al. (1998), Wen et al. (2000), Zhang (2005), Zhang (2006).
		Subsurface dam	Huang and Pang (2013), Liu et al. (2004), Shi and Jiu (2014), Sun et al. (2006), Wang et al. (2012), Zhang and Wang (2011), Zhou et al. (2014).
		Sand and storage dam	
		Channel spreading	
	Rainwater & run-off harvesting	Rooftop rainwater harvesting	He (2012), Wang (2012), Yan (2009), Zhang et al. (2013), Zhu (2012), Zhu (2013).
		Barriers & bunds	
		Trenches	

increasing; the methods of dug well/shaft/pit injection and the subsurface dam had also been commonly applied in China since 1980s; while the induced bank infiltration method was no longer used after 1980s.

China had been extracting water from different sources for artificial groundwater recharge, for example, rainwater, lakes & artificial reservoirs, perennial streams and river water (Table 3). Among these sources, perennial streams and rainwater were the most frequently used, accounting for nearly two-thirds of the total number of sources for groundwater recharge, with perennial streams contributing 40.5% and rainwater contributing 25%. River water ranked the third source which had a percentage of 13.5% of the total water sources for the MAR projects. However, reservoir water, groundwater, tap water and treated waste water were much less used in MAR, e.g. 8.7% of the total influent sources was contributed by groundwater; 4.8% was taken from the reservoir water, according to the studies from Jia and Li (2012) and Qu (2014), which had the same percentage as the treated waste water; tap water was the least used and was only discussed by Yang et al. (2010) and Wu et al. (2010).

Among the 136 MAR cases, aquifer conditions (material composition and confinement) were discussed in 93 sites (68%). In China, only fluvial deposits and karstic carbonate were selected as favourable aquifer conditions for groundwater recharge (Fig. 6). When using spreading method, only fluvial deposits could be considered to develop MAR projects. A typical application was carried out by Guan et al. (2015), who introduced the reverse drainage method in Boxing, Shandong. Fluvial deposits and karstic carbonate were also the most favourable targets when using the me-

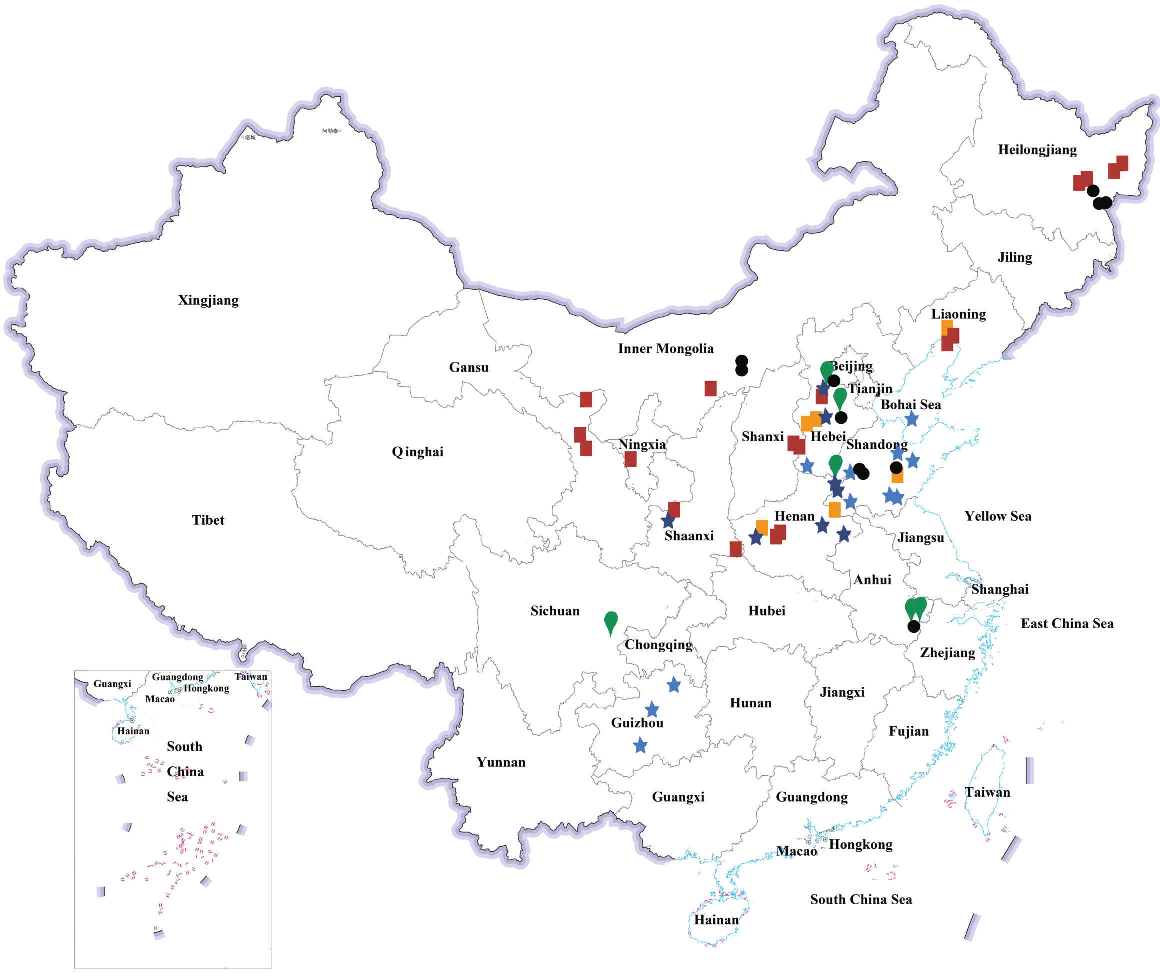

Fig. 1 General distribution of the MAR projects in China (base map from http://bzdt.ch.mnr.gov.cn)

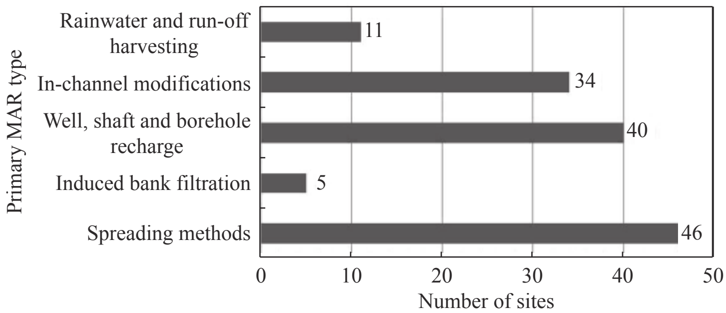

Fig. 2 Number of the primary MAR case types

thods of well, shaft & borehole recharge, in-channel modification and rainwater harvesting for MAR projects. Other applications included Wen et al. (2000) and Zhang (2005) with the method of recharge dam, Shi and Jiu (2014) with the method of subsurface dam, Wang and Qu (2014) with the ASR/ASTR, He (2012) and Zhu (2012) with the method of roof rainfall water harvesting, and Li et al. (2012) with the method of dug well/shaft/pit injection. Though aquifer material conditions were limited to only two types in these MAR practices, the successful experience could still be shared with other areas with these two types of aquifer conditions.

Furthermore, among those 93 sites in China, unconfined aquifer was the most commonly selected aquifer type for groundwater recharge (Fig. 7) when using the spreading method (Li et al. 2011; Huang and Pang, 2013), in-channel modification (Sun et al. 2006; Huang and Pang, 2013; Wang et al. 1999; Han, 2002) and rainwater & rooftop harvesting. Out of the 28 cases using the

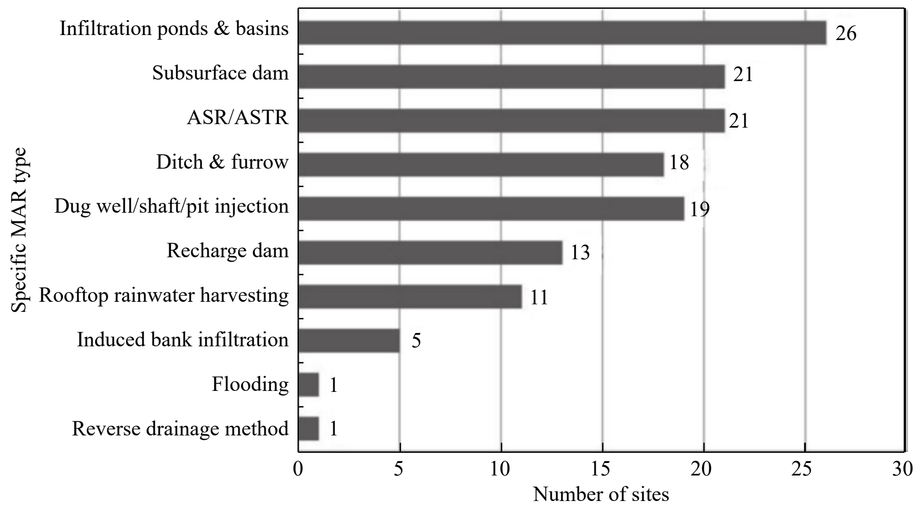

Fig. 3 Numbers of different specific MAR cases in China

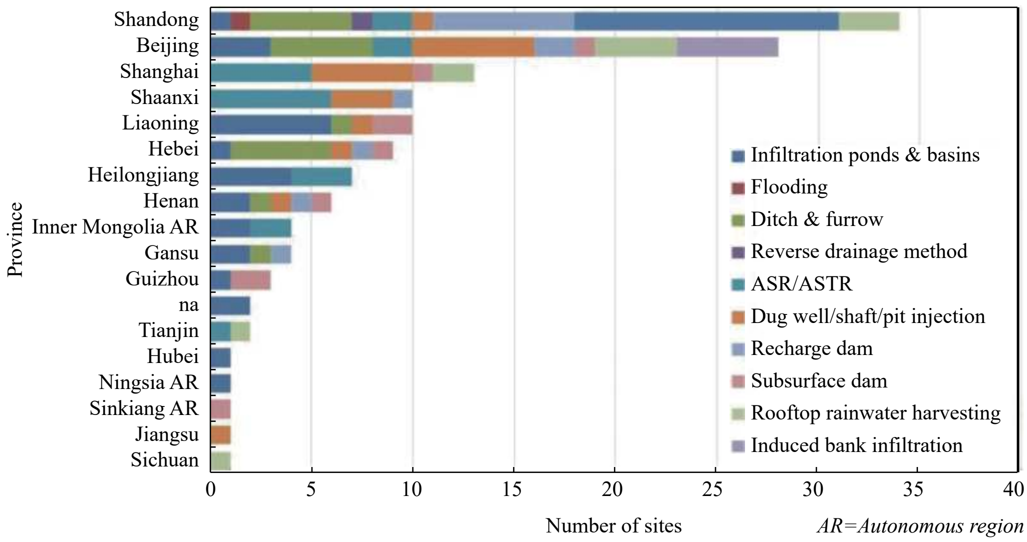

Fig. 4 Distribution of specific MAR cases in different provinces and municipalities

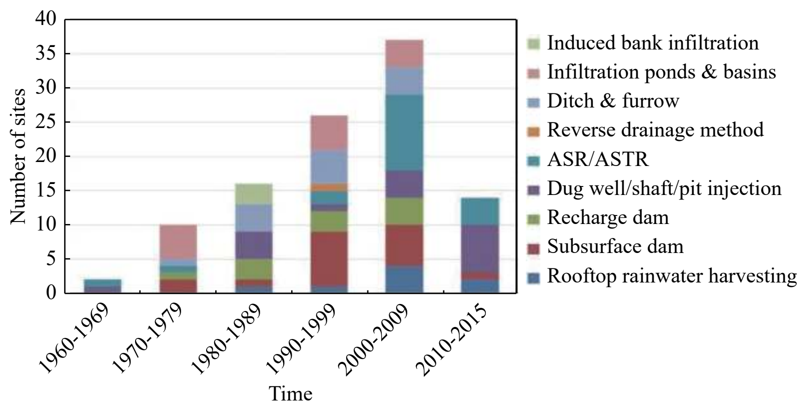

Fig. 5 Development of the MAR projects in China after 1960

method of well, shaft & borehole recharge, 13 of them were applied in unconfined aquifer (Zhang et al. 2007; Yang et al. 2010; Zhao et al. 2004) and 15 in confined aquifers, as reported by Dong et al. (2011), Dong (2010) and Su (2012) in Xi'an City; Liu and Dai (2013) in Shenyang; Lu and Pan

Table 3 Percentage of the water sources used in the MAR projects in China

Water source of MAR projects	Percentage of the water sources in all the MAR projects in China	Collected literatures
Rainwater	25.0%	Ding (1997), He (2012),Huang and Pang (2013),Li et al. (2011), Su et al. (1996), Wang (2012),Yan (2009), Zhang et al. (2013), Zhao et al. (2004), Zhu (2012), Zhu (2013),
Lakes & artificial reservoirs	4.8%	Jia and Li (2012), Qu (2014).
Perennial streams	40.4%	Ding (1996), Dong (2010), Guan et al. (2015), Han (2002), Hao (2011), Huang and Pang (2013), Jin et al. (2012), Li (2009), Liu et al. (2004), Liu et al. (2006), Liu and Dai (2013), Liu and Song (1989), Shi and Jiu (2014), Su (2012), Su et al. (2010), Su et al. (2014), Sun et al. (2006), Wang et al. (2012), Wang et al. (2001),Wang et al. (1998), Wang and Qu (2011), Wang and Zhang (1991), Wen et al. (2000), Yang et al. (2010),Yuan (1979), Zhang (2005), Zhang et al. (2013), Zhang (2006), Zhang and Wang (2011), Zhou et al. (2014).
Tap water	2.9%	Wu et al. (2010), Yang et al. (2010).
Aquifer (groundwater)	8.7%	Bai et al. (2010), Fan (2014), Liu et al. (2006), Liu and Pan (2014), Lu et al. (2014), Qu et al. (2012), Yan et al. (2014), Zhang et al. (2011).
Treated waste water	4.8%	Dong et al. (2011), He and Shen (2010), Jin et al. (2012), Li et al. (2012), Pi and Wang (2006), Wei et al. (2014), Xu et al. (2012), Zhang et al. (2007).
River water	13.5%	Han (2002), He and Shen (2010), Huang and Pang (2013), Shi and Jiu (2014), Wang et al. (1999), Wang et al. (2012), Zhang (2005).

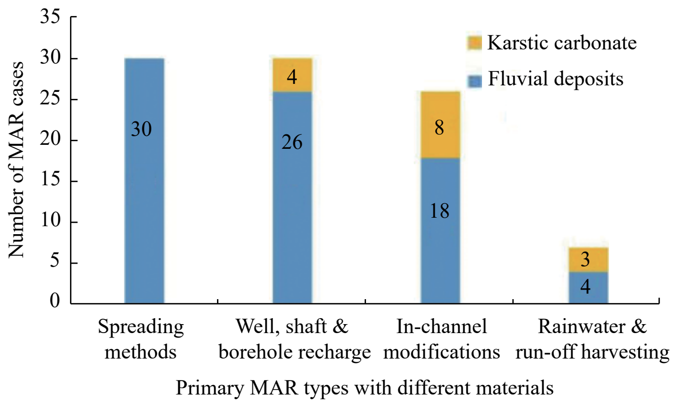

Fig. 6 Primary MAR types with aquifer materials

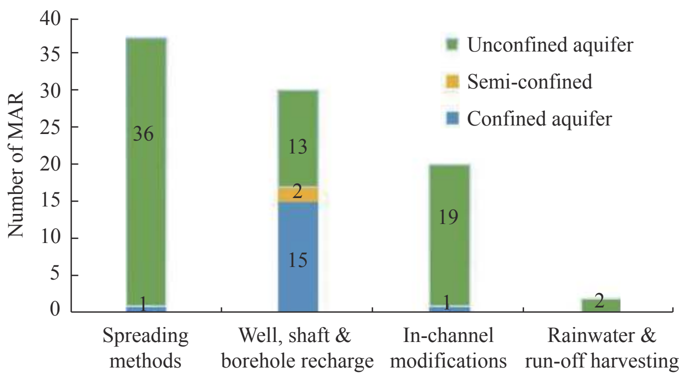

Fig. 7 Primary MAR types with aquifer types

(2014) and Qu et al. (2012) in Shanghai; Zhao et al. (2004) in Sanjiang Plain;Wang and Qu (2014) in Jinan City.

MAR was applied in China for four main purposes, i.e. ecology & environment, agriculture, industrial and domestic use (Fig. 8). Nearly half of the recharged water resource had been contributed to the ecological and environmental purpose which

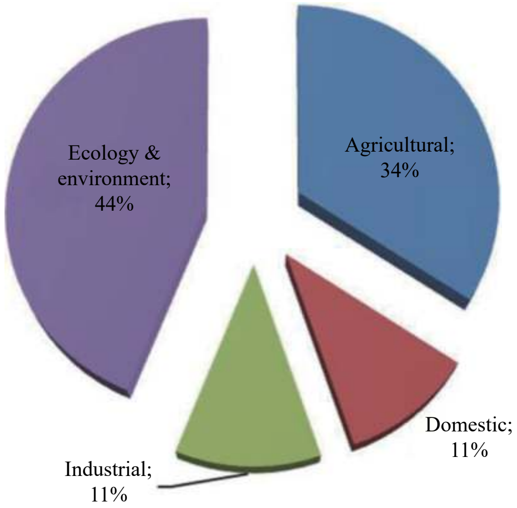

Fig. 8 Percentage of different uses of the extracted water from the recharged aquifers

took the highest percentage of the whole water use. Agriculture irrigation ranked the second biggest water user from MAR, which consumed around one-third of the total resources from MAR. The rest 22% of water from MAR was divided equally by industrial use as mentioned by Wen et al. (2000), Wang and Qu (2011) and Jin et al. (2012), and by domestic consumptions in Shangdong (Guan et al. 2015), Anhui (Li, 1997), Beijing (Zhang et al. 2013), Xi' an (Hao, 2011), and Shengyang (Su et al. 1996). This allocation could be possibly explained by the fact that requirement on water quality for the ecological, environmental and agricultural purpose was not as high as for industrial and domestic use; therefore, the recharged water was directly pumped from the recharged aquifers and transferred to the natural field and some factories without further treatment.

3 Discussion

Assessment of the feasibility of MAR projects in the local area should include the identification of current water stress level (i.e. storage and demand), water availability (e.g. excess surface water flows, treated waste water), groundwater quality, prevention of potential land subsidence and energy storage efficiency (Clifton et al. 2010). In this review, the following achievements were summarized from the assessment of MAR projects in China:

1) Well-canal combination project was found to be the best way to ensure water supply for agricultural irrigation in most rural areas in northern China (Wang et al. 2010).

2) The underground reservoirs built on river bed in the coastal plain area successfully prevented seawater intrusion and increased water supply by promoting infiltration facilities such as surface barrage, seepage well and infiltration gallery (Wang et al. 2010).

3) The aquifer was found to be very useful on the treatment of reclaimed water source at one study site in Beijing (especially on the removal of bacteria, BOD and COD); recharging better quality of surface water into the aquifer by the spreading method was also successfully applied to improve the groundwater quality (Zhang et al. 2013).

4) In order to prepare for any emergency related to groundwater ecological environment, the reservoirs in upstream had been used as an effective facility to control water discharge and seepage from the river channel and increase water resource in downstream (Wang et al. 2010).

5) MAR was applied to control land subsidence successfully (Qu et al. 2012); and the aquifer had been confirmed being able to keep water warm or cool within the aquifer thermal energy storage system in the city (Wu, 2004).

In addition, a scientific and applicable system for the development of a new MAR project in China is depicted in Fig. 9 (Jin et al. 2012). Comprehensive field investigation, relevant environmental protection laws, reliable groundwater monitor systems, such as the groundwater level and quality monitoring, were incorporated into the whole MAR system to ensure a sustainable implement of the project. In addition, more efforts could be made to assess the environmental impact of the MAR project in order to avoid the negative influence from the 'disturbed' aquifer system on the surrounding environment. A new MAR project and corresponding monitor systems should be developed upon the approval of relevant authorities.

Although China had accumulated rich experience of MAR, there were still many challenges in this field. Some common ones are listed below:

1) More MAR project were needed in the high risk areas, e.g. Jiangsu Province.

According to the data from National Bureau of Statistics in China, Jiangsu Province were among the regions which had the highest population density and largest contribution to the national economy but also with the highest risk of groundwater shortage. In addition, due to the large amount of groundwater usage, severe land subsidence had occurred in some cities like Suzhou and Wuxi, where the deepest subsidence was found to be 1.08 m (Guo et al. 2004). However, from the literature review, very few MAR projects had been implemented in Jiangsu Province. Therefore, it is

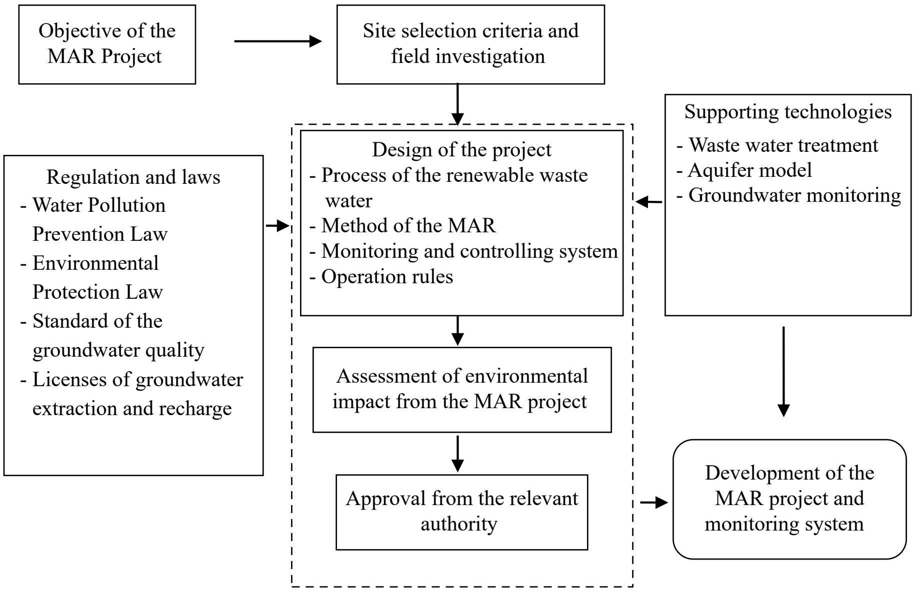

Fig. 9 General framework to develop an MAR project (adapted from Jin et al. 2012 with permission)

recommended that more MAR projects should be promoted in Jiangsu Province in order to alleviate the situation of water stress and land subsidence.

2) Lack of studies on water quality for MAR

In coastal areas, the untreated sewage had posted a great threat to the water quality of underground reservoirs as upstream pollutions were out of control. In addition, there was a lack of study on aquifer recharge with urban reclaimed water. Water quality should be studied through monitoring and sampling on site and numerical simulation (Wang et al. 2014).

3) Usage of treated waste water

As being shown in Fig. 6, treated waste water had not been widely used in groundwater recharge. According to the report from the MOHURD, by the end of Year 2014, 3 717 waste water treatment plants were built up and in 2014 a total of 48.06 billion m^3 of waste water was treated and high percentage of it was directly discharged into the nearby rivers (Jin et al. 2012). It is suggested that the treated waste water could be used in the MAR projects to save local water resources.

4) Imperfect systems of MAR

Although some regulations for MAR project management had been stipulated in China, for example, the deep well management regulation in Shanghai and the Interim Regulation for Groundwater Resources Management in Beijing; more scientific and comprehensive administration systems on MAR were still to be developed. In this case, a series of technical criteria for the evaluation, construction and project management for MAR were highly recommended in the near future (Wang et al. 2014).

4 Conclusions

In the past decades, China had managed to make great achievements in land subsidence control, energy storage, prevention of seawater intrusion, increasing urban water supplies, agriculture irrigation and alleviation of agricultural disasters through the implementation of MAR projects (Wang et al. 2014). From the successful experience, a scientific and applicable framework was summarized to develop a new MAR project. However, there were still many challenges, for example, very little treated waste water had been used in MAR projects and very few MAR projects were implemented in areas with extremely high risk of water shortage. More scientific and comprehensive administration systems on MAR were still to be developed. More feasible, convenient and economic techniques of MAR needed to be developed to fit the local hydrogeological conditions in a better way. Proper guidelines and regulations for MAR management were also necessary to ensure the smooth operation of MAR projects (Wang et al. 2014).

It should be noted that this study mainly focused on the MAR projects published before 2016 and a subsequent review is on the schedule for those projects published after the year 2016 as a continuation of this study.

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