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Sustainability of groundwater usage in northern China: dependence on palaeowaters and effects on water quality, quantity and ecosystem health

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Abstract:

A synthesis of groundwater ages, recharge rates and information on processes affecting groundwater quality in northern China highlights the major challenges faced for sustainable management of the region's groundwater. Direct recharge rates range from hundreds of millimetres per year in the North China Plain, to tens of millimetres per year in the Loess Plateau to less than 4 mm/year in the arid northwest. Recharge rates and mechanisms to deep semiconfined and confined aquifers are poorly constrained; however, on the basis of available data, these are likely to be mostly negligible. Severe groundwater level declines (0.5–3 m/year) have occurred throughout northern China in the last three to four decades, particularly in deep aquifers. Radiocarbon dating, stable isotope and noble gas data show that the most intensively extracted deep groundwater is palaeowater, recharged under different climate and land cover conditions to the present. Reservoir construction has reduced surface runoff in mountain-front areas that would naturally recharge regional Quaternary aquifers in many basins. In combination with intensive irrigation practices, this has resulted in the main recharge source shifting from surface runoff and mountain-front recharge to irrigation returns. This has reduced infiltration of fresh recharge at basin margins and rapidly increased nitrate concentrations and overall mineralisation in phreatic groundwater over wide areas (in some cases to >400 mg/l and >10 g/l, respectively). In some basins, there is evidence that poor quality shallow water has leaked into deep layers (>200 m) via preferential flow, mixing with palaeowaters stored in semiconfined aquifers. High concentrations of naturally occurring fluoride and arsenic (locally >8.5 and >4 mg/l, respectively) have recently lead to the abandonment of numerous supply wells in northern China, creating further pressure on stressed water resources. Increasing water demand from direct and indirect consumption poses major challenges for water management in northern China, which must consider the full water cycle. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS Groundwater; China; Sustainability; Palaeowaters; Recharge; Water quailty

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INTRODUCTION

China has the world's largest population and will soon be the world's largest economy. The challenge of managing China's water resources sustainably is a crucial national and global issue, with broad implications for food security, human health and social stability (Liu and Xia 2004; OECD, 2007; Cai 2008; Gleik, 2009; Schneider, 2011). The issue of unsustainable groundwater usage has been recognised within China and in the international community as a major pressing issue (Qiu, 2010), while global interest in groundwater sustainability is increasing as attempts are made to understand the effects of global change (including climate change) on the water cycle (Green *et al.*, 2011). Half of China's land area is arid or semiarid, with approximately one quarter receiving less than 200 mm of rain per year. Nearly all of the arid and semiarid areas are in northern China, which contain approximately half of China's population but less than 15% of its available surface water (OECD, 2007). In the past 50 years, groundwater has been the key factor that has allowed agricultural production in northern China to increase in output and expand in area. Increasing urbanisation and sustained rapid economic growth in China are being accompanied by increased water demand, including direct consumption and indirect and induced consumption (e.g. from energy production and demand for water-intensive products, Cai, 2008; Zhu *et al.*, 2009; Schneider, 2011). China's policy of grain self-sufficiency also ensures high demand for agricultural water in northern China (Bradsher, 2011). In this context, the issue of the sustainability of groundwater usage and the future role of groundwater in supplying northern China's water is of vital importance. Addressing this issue requires an understanding of groundwater ages, recharge rates and recharge mechanisms (Scanlon *et al.*, 2006; Gleeson *et al.*, 2010), the major processes affecting groundwater quality (Edmunds, 2009) and groundwater's relationship to the wider water-cycle and eco-environments

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(Hancock *et al.*, 2010). These are the topics of this review, focusing on the arid and semiarid areas of northern China (Figure 1).

The history of groundwater usage in China dates back to 3750 BCE, and it has played an important role in supplying water since historical records began (Elvin, 2004; Zhou *et al.*, 2011a). Currently more than 40% of water used in northern China is groundwater (OECD, 2007). Since the late 1950s, numerous bore fields and wells have been developed to pump hundreds of billions of cubic metres of water per year, which together with dams and surface water diversion schemes supply nearly all of the region's water. The development of groundwater facilitated enormous increases in agricultural production in the North China Plain and provinces in the north-central regions (e.g. Shanxi and Shaanxi) and allowed the expansion of agriculture to marginal, arid environments in northwest China, such as Inner Mongolia and Gansu Province, where large agricultural 'oases' have developed on the basis of groundwater pumping (Cui and Shao, 2005; Ma *et al.*, 2005; Chen *et al.*, 2006b; Wei *et al.*, 2010; Huo *et al.*, 2011). In the last decade, several serious groundwater resource problems have emerged in northern China, including overexploitation and deteriorating quality, threatening both agricultural and domestic water supplies. These problems are affecting millions of people and many high-value ecosystems (OECD, 2007; Gleik, 2009; Shen and Chen, 2010; Zheng *et al.*, 2010).

There is currently a heavy reliance on deep groundwater reserves in Quaternary aquifers, ranging from thick unconfined aquifers (large inland river basins of northwest China) to multilayered semiconfined and confined aquifers. These resources are exploited to support intensive irrigated agriculture, yet many have been shown to comprise palaeowaters, recharged thousands or tens of thousands of years ago (Chen *et al.*, 2003; Edmunds *et al.*, 2006; Gates *et al.*, 2008a, 2008b; Zhu *et al.*, 2008; Kreuzer *et al.*, 2009; Chen *et al.*, 2010; Currell *et al.*, 2010; Chen *et al.*, 2011). In some cases, particularly in arid desert regions of northwest China, there is strong evidence that little or no present-day recharge is occurring to deep aquifers that are used or proposed for use as water supplies (Edmunds *et al.*, 2006; Gates *et al.*, 2008a; Ma *et al.*, 2009a; Ma *et al.*, 2010). Regardless of whether any modern recharge currently reaches deep aquifers or not, the decline in deep groundwater pressures seen across northern China indicates that the recharge–discharge balance has been fundamentally altered and that pumping has created a massive deficit between extraction and replenishment. Another major problem that has received less attention is that the dominant recharge source to many unconfined aquifers has shifted from rainfall and surface water runoff to direct recharge via infiltration of irrigation water, which is typically more saline and contains higher concentrations of nitrate and other contaminants than natural recharge (Kendy *et al.*, 2004; Currell *et al.*, 2010; O'Dochartaigh *et al.*, 2010). Particularly in arid areas of northwest China, where potential evapotranspiration far exceeds precipitation and runoff, this shift has had a major effect on water and salt balances, which in turn has created problems of soil salinity, desertification and ecosystem degradation (Cui and Shao, 2005; Ma *et al.*, 2005; Pang *et al.*, 2010).

This article reviews the literature reporting groundwater ages, recharge rates, groundwater quality data and information on the processes affecting water quality and groundwater-dependent ecosystems in the major aquifers of northern China. There is a particular emphasis on studies that have made use of geochemistry, including environmental isotopes. Environmental tracers are suited to understanding current and past hydrological processes in arid or semiarid regions, where there are large uncertainties associated with estimating the water balance (Scanlon *et al.*, 2002; Scanlon *et al.*, 2006; Edmunds,

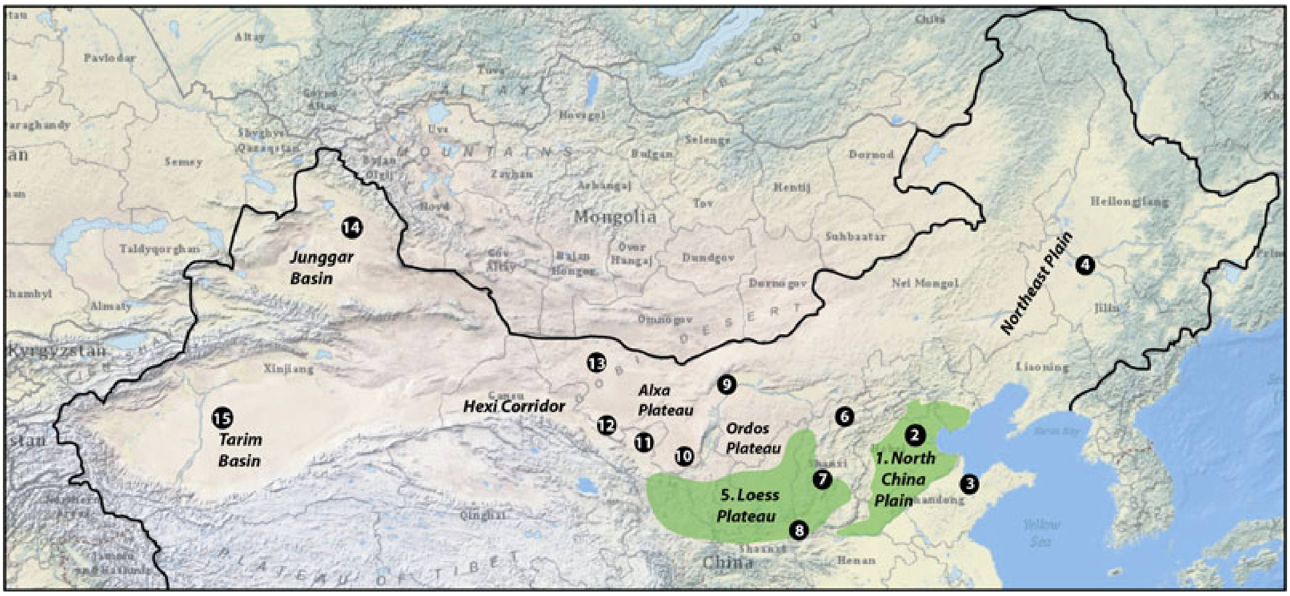

Figure 1. Locality map of northern China, showing locations where groundwater ages, recharge rates, groundwater level declines and groundwater quality data have been reported (locality numbers correspond to key in Tables I and II)

2009; Herczeg and Leaney, 2011).Through synthesis of the data and examination of a range of case studies, the major problems and future challenges for sustainable groundwater management in northern China are identified, falling into three broad categories, which are discussed separately: Reliance on Palaeowaters and Imbalance between Recharge and Extraction section, Deterioration of Groundwater Quality section and Environmental and Ecosystem Degradation section. Current water management strategies and recent progress in addressing these issues are also discussed, along with an assessment of measures that could help to achieve sustainable groundwater management in northern China in the coming years.

Hydrogeologic settings in northern China

Northern China includes numerous geographical and hydrogeological environments; a comprehensive review of these settings is beyond the scope of this article, and readers are directed to consult the references in Tables I and II and in-text for details on specific regions. Some general comments can be made regarding regional hydrogeological settings. Northern China can be broadly divided into three major geographic/geologic province: (i) northeast, including the North China Plain and Northeast (Songnen) Plain; (ii) central, including the Loess Plateau, Ordos Plateau and six basins of Shanxi; and (iii) northwest, including the Alxa Plateau, Hexi corridor, Tarim and Junggar Bains (Figure 1; Ma *et al.*, 2002). Precipitation broadly decreases from east to west, from >600 mm/year in the northeast to <100 mm in the far northwest. Rainfall throughout northern China is largely controlled by the East Asian Monsoon, and most precipitation occurs in summer (July to September) in association with the southeast monsoon, including in much of the hyperarid northwest.

Most groundwater resources in northern China are extracted from unconsolidated Quaternary sedimentary aquifers, typically deposited in fault-subsidence basins adjacent to mountain ranges composed of Palaeozoic to Mesozoic (locally Proterozoic and Archaean) rocks (Ma *et al.*, 2002). The Quaternary sedimentary sequences are typically made up of interlayered fluvial, lacustrine and aeolian deposits ranging from coarse sands and gravels to silts and clays. Typically, sediments grade from coarse alluvium/diluvium near mountain-front piedmont plains to finer alluvial plain/lacustrine sequences on the distal sedimentary plains. Aeolian sediments (loess) occur in variable amounts within these sequences reflecting periods of major dust storm activity. In several cases, thick (up to hundreds of metres), high permeability unconfined aquifers occur at the basin margins, grading into confined and semiconfined aquifer units at depth and away from the mountain front, as fine horizons increasingly predominate within the sedimentary sequences. The Quaternary sediments of northern China are divided into four major stratigraphic units (lower, middle and upper Pleistocene and Holocene), denoted Q_1–Q_4, within which are several local subdivisions. Typically, Q_3 and/or Q_4 sediments constitute the uppermost unconfined aquifers, whereas Q_1 and Q_2 sediments make up semiconfined or confined aquifer units. These are the layers that typically contain the high-quality palaeowaters that are intensively extracted as water resources, as discussed in the following sections.

Reliance on palaeowaters and imbalance between recharge and extraction

Palaeowaters are groundwater resources that were recharged in premodern times, under different climatic or hydrological regimes than the present (Clark and Fritz, 1997). In the last 5 to 10 years, several studies have shown that deep sedimentary aquifers throughout northern China (mostly semiconfined or confined aquifers) contain groundwater recharged during the Late Pleistocene and Early Holocene periods (Chen *et al.*, 2003; Edmunds *et al.*, 2006; Gates *et al.*, 2008a; Kreuzer *et al.*, 2009; Ma *et al.*, 2009a, 2009b; Currell *et al.*, 2010; Han *et al.*, 2010a; Ma *et al.*, 2010; Chen *et al.*, 2011). Palaeowaters, identified by radiocarbon dating, stable isotope analysis and (in some cases) measurement of noble gases, are exploited at high rates throughout northern China, mostly to provide water for irrigation (Ma *et al.*, 2005; Edmunds *et al.*, 2006; Kreuzer *et al.*, 2009; Chen *et al.*, 2010; Currell *et al.*, 2010; O'Dochartaigh *et al.*, 2010). The drilling of major well fields and the exploitation of deep groundwater mostly began in the 1960s, increasing through the 1970s and 1980s. In northwest China, this was tied to policies of resettling people to sparsely inhabited areas, where artificial agricultural oases were established on the basis of bore field development and dam construction, and these continue to rely heavily on groundwater (e.g. Ma *et al.*, 2005; Ma *et al.*, 2009a; Wei *et al.*, 2010).

Table I presents a summary of major aquifer systems in northern China for which groundwater ages and recharge rates have been estimated, with locations shown in Figure 1. Rates of groundwater level decline are also listed from areas where monitoring data have been reported, although there is no national public database reporting groundwater level data in China (Qiu, 2010). In all cases, there has been significant drawdown of water levels in deep confined, semiconfined and/or unconfined aquifers (Table I), with an overall range of decline between approximately 0.2 and approximately 4 m/year (Figure 2). The declines are particularly severe near large urban centres northeast China, where major cones of depression have formed below cities (e.g. Foster *et al.*, 2004; Zhang *et al.*, 2009a). For example, in the confined aquifer of the North China Plain, depth to water had reached 87 m in the cone of depression below Hengshui and 109 m below Cangzhou in 2005, causing fracturing and land subsidence in these areas (Chen *et al.*, 2010). The water level declines are widespread and not confined to urban areas; Zhang *et al.* (2009b) estimated that the area in which the deep aquifer below the North China Plain was subject to rapid water level decline since 1991

Table I. Groundwater ages, water level declines and estimated recharge rates for major aquifers of northern China

Map no.	Basin/region	Aquifer unit	Groundwater age range	References	Water level decline (m/year)	References	Recharge rate (mm/year)	Type of recharge estimated	Method	References
1	North China Plain	Unconfined, including mountain-front piedmont	Modern (decades)	Kreuzer *et al.* (2009), Von Rohden *et al.* (2010)	Up to 1.5	Foster *et al.* (2004), Wang *et al.* (2009)	~300	Direct and focussed	Tritium–helium	von Rohden *et al.* (2010)
							50–1090; 60–250	Direct (irrigation + precipitation)	Soil–water balance; applied tracers	Kendy *et al.* (2004), Wang *et al.* (2008)
		Deep confined	Modern to >35 ka	Kreuzer *et al.* (2009), Chen *et al.* (2003), Zhang *et al.* (2009c)	2–3	Liu and Xia (2004)				
2	Baiyangdian wetland	Shallow unconfined	Modern	Moiwo *et al.* (2010)	~1		50–143	Direct	Water balance/ model	Moiwo *et al.* (2010)
3	Laizhou Bay	Shallow unconfined	Modern to ~3 ka	Han *et al.* (2011a,2011b)	0–1.2	D.M. Han (unpublished results)		Direct and focussed		
		Deep confined	7.5–22 ka		0.25–1.2					
4	Songnen Plain	Shallow unconfined	Modern (decades)	Chen *et al.* (2011)			2–11	Horizontal flow	Radiocarbon	Chen *et al.* (2011)
		Deep confined	Modern to ~25 ka							
5	Loess Plateau	Shallow unconfined	Modern	Lin and Wei (2006), Gates *et al.* (2011)	~1	Huang and Pang (2011)	33–~100	Direct and focussed	Tritium and Cl MB	Lin and Wei (2006), Huang and Pang (2011), Gates *et al.* (2011)
8	Yuncheng Basin	Deep semiconfined	3.5–22 ka	Currell *et al.* (2010)	1–3.2	Cao (2005a)				
10	Alxa Zuoqi Oases	Deep unconfined	0.3–15 ka	D.C. Bradley (unpublished results)	0.5–4	O'Dochartaigh *et al.* (2010), D.C. Bradley (unpublished results)				
11	Minqin Basin	Shallow unconfined					2.8	Direct	Cl MB	Edmunds *et al.*, 2006
		Deep semiconfined and confined	0.6–85.5 pmc (modern to Pleistocene)	Edmunds *et al.* (2006)	<1–1.8	Edmunds *et al.* (2006), Ma *et al.* (2005), Huo *et al.* (2011)				

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12	Badain Jaran and Southern Gobi Desert	Piedmont/ unconfined aquifer	Modern to hundreds of years	Gates *et al.* (2008a), Ma *et al.* (2009a, 2009b)			0.95–3.6	Direct	Cl MB	Ma and Edmunds (2006), Gates *et al.* (2008b)
		Deep confined aquifers	Modern to 27 ka	Gates *et al.* (2008a), Ma *et al.* (2010)						
13	Heihe Basin	Shallow unconfined	Modern (decades)	Zhu *et al.* (2008), Chen *et al.* (2006a)	0–~1	Zhou *et al.* (2011b)	15.4 x 10^8 m^3/year	Rainfall + Irrigation	Model	Zhou *et al.* (2011b)
		Deep confined	Modern to 11 ka							
15	Tarim Basin	Unconfined	Modern and premodern	Huang and Pang (2011)						

Groundwater age estimates are based on radiocarbon and tritium; recharge rates are estimated using water balance, tritium, radiocarbon and Cl MB techniques. Localities shown in Figure 1. Cl MB, chloride mass balance.

accounts for 62% of the total area of the plain (~70 000 km^2). Many other basins have experienced water level declines of similar or greater magnitude, particularly in deep aquifers (Table I) and in both agricultural and urban areas. Groundwater depletion has also affected surface water; for example, in the piedmont of the Junggar basin, the water table has fallen by 5 to 10 m in recent years, which has shifted the location of spring occurrence downgradient by between 2 and 5 km (Chen *et al.*, 2010).

Groundwater recharge history and recharge rates. Radiocarbon data show that a substantial proportion of heavily exploited groundwater in deep aquifers was recharged thousands or tens of thousands of years ago (e.g. radiocarbon activities below ~60% modern carbon). In most cases, shallow unconfined aquifers contain modern groundwater, whereas groundwater ages increase with depth, in some cases to beyond the age limit of radiocarbon dating (approximately 35 ka). In the Minqin Basin (northwest China) and North China Plain (in northeast China), it has been shown through the determination of noble gas recharge temperatures that a substantial proportion of groundwater in deep confined layers was recharged under a climate between approximately 2 °C and 5 °C cooler than the present (Edmunds *et al.*, 2006; Kreuzer *et al.*, 2009). The lower temperatures during recharge of this groundwater are also indicated by more depleted stable isotope compositions (δ^2H and $\delta^{18}O$) in groundwater with low radiocarbon activities (e.g. <20 pmc, which approximately corresponds to the Pleistocene–Holocene transition in northern China; cf. Edmunds *et al.*, 2006). Although the measurement of noble gases has only been conducted in these two areas, depleted stable isotopes in deep groundwater have been documented in many basins, including the Heihe Basin (Chen *et al.*, 2006a; Zhu *et al.*, 2008), the Yuncheng Basin (Currell *et al.*, 2010), the Alxa League Oases (O'Dochartaigh *et al.*, 2010), the Songnen Plain (Chen *et al.*, 2011), the Taiyuan and Ordos Basins and the Yinchuan Plain (Huang and Sun, 2007) (Figure 3). The relationship between recharge temperature and stable isotope composition is complicated because δ^2H and $\delta^{18}O$ are influenced by other processes, including intensity of precipitation, evaporation before recharge and altitude (e.g. Johnson and Ingram, 2004; Yamanaka *et al.*, 2004; Han *et al.*, 2010a). However, the regional trend in stable isotopes of groundwater that has been dated indicates that a large proportion of deep groundwater in northern China was recharged under a different (cooler) climate than the present. Geothermal waters, such as those exploited in the Xinzhou Basin of Shanxi, are also unique palaeowaters, which are typically older than the limit of ^{14}C dating, and belong to major deep regional flow systems (Han *et al.*, 2010a). The age and recharge mechanism of these waters is generally poorly studied and an area for future research.

Two major questions are of great relevance to the sustainability of groundwater usage in northern China.

Table II. Groundwater quality indicators from major aquifers in northern China

Map key	Basin/region	Aquifer unit	NO_3 (range, mg/l)	TDS (range g/l)	Fluoride (range mg/l)	Arsenic (range, μg/l)	References
1	North China Plain	Unconfined	nd to 320; mean of 45.3	0.5–1 g/l (piedmont); 1–3 g/l (central); 3–5 g/l (eastern); >5 g/l (coastal)			Chen *et al.* (2005), Lu *et al.* (2008), Zhang *et al.* (2009c)
3	Laizhou Bay	Shallow unconfined	7 to 346	0.5 to 144 g/l[a]			D.M. Han (unpublished results)
		Deep confined	nd to 228.5	0.5 to 125 g/l[a]			D.M. Han (unpublished results)
4	Songnen Plain	Shallow unconfined	nd to 594				Chen *et al.* (2011)
6	Datong Basin	Shallow unconfined	nd to 517	0.25 to 8.9 g/l	0.1 to 8.9	<1 to 1932	Guo *et al.* (2003), Guo and Wang (2005)
7	Taiyuan Basin	Shallow and deep	nd to 52	Up to 8 g/l	0.4 to 6.2	0.74 to 115.5	Guo *et al.* (2007a,b)
8	Yuncheng Basin	Shallow unconfined	nd to 190	0.7 to 8.5 g/l	0.1 to 11.2	<1 to 4800	Currell *et al.* (2011), Currell *et al.* (2010), Cao (2005b)
		Deep semiconfined	nd to 43	0.5 to 1.8 g/l	0.3 to 4.1	<1 to 27	
9	Huhhot Basin	Shallow	<0.5 to 34[b]	~0.3 to 3 g/l	0.14 to 6.8	<1 to 1480	Smedley *et al.* (2003), Mukherjee *et al.* (2009)
		Deep confined	<0.5 to 6.1		0.13 to 2.4	<1 to 308	
10	Alxa Zuoqi Oases	Unconfined alluvial aquifer	5 to 305	0.5 to 6.2 g/l	0.1 to 1		O'Dochartaigh *et al.* (2010); D.C. Bradley (unpublished results)
11	Minqin Basin	Shallow unconfined		Up to 5 g/l	Up to 26		Ma *et al.* (2005), Wang and Cheng (2001)
		Semiconfined and confined aquifer	<7	~0.5 to 6 g/l	<1.35		Edmunds *et al.* (2006), Ma *et al.* (2005)
13	Heihe Basin	Shallow unconfined	2.7 to 45.8	0.35 to 5 g/l	Up to 18.6		Zhu *et al.* (2008), Zhu *et al.* (2010), Wang and Cheng (2001)
		Deep confined	2.1 to 7.2	0.3 to 2.3 g/l	<0.4		
14	Junggar Basin	Unconfined		0.5 to 77 g/l	Up to 4	Up to 750	Wang *et al.* (1986), Wang and Cheng, 2001, D.M. Han (unpublished results)
15	Tarim Basin	Unconfined	nd to 5	0.7 to 55 g/l	0.3 to 10.4		Huang and Pang (2010), Pang *et al.* (2010)

nd, not detected/below detection limit.

[a] Affected by seawater intrusion and storage of ancient brine.

[b] Also nitrite and ammonia present in reducing waters.

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First, what are typical present day groundwater recharge rates? Second, does recharge reach the deep aquifers which are the target of a large amount of pumping? There is a good understanding of recharge rates and mechanisms for shallow unconfined aquifers, and rates of direct recharge have been estimated for many regions (Table I). The most common approaches used have been soil–water balance modelling (e.g. Kendy *et al.*, 2003; Kendy *et al.*, 2004), application of conservative tracers to the soil (e.g. ^{3}H and Br, Wang *et al.*, 2008), measurement of tritium and chloride in unsaturated zone moisture profiles (e.g. Lin and Wei, 2006; Gates *et al.*, 2008b; Gates *et al.*, 2008c; Ma *et al.*, 2009b; Gates *et al.*, 2011; Huang and Pang, 2011) and ^{3}H-He dating (von Rohden *et al.*, 2010). In general, direct recharge decreases with increasing aridity from the North China Plain (approximately hundreds of millimetres per year; range = 50–1090 mm/year) to lower rates in the Loess Plateau (approximately tens of millimetres per year; range = 33–100 mm/year) to negligible rates in northwest China (range = 0.95–3.6 mm/year). It should be noted that depending on the technique used, these rates can represent modern or past recharge rates; for example, soil–water balance and applied tracer studies of the North China Plain (Kendy *et al.*, 2004; Wang *et al.*, 2008) are representative of modern rates and recharge predominantly by irrigation; chloride profile–derived rates from northwest China (e.g. Gates *et al.*, 2008c; Ma *et al.*, 2009b) are representative of recharge rates integrated over the last hundreds of years. Chloride-based recharge estimates in northwest China and the Loess Plateau also contain information about changes in recharge over these periods (from decades up to ~2 k.a.), showing that both climatic change (periods of greater/lesser aridity) and land-use change (e.g. soil conservation measures in the Loess Plateau) have resulted in measurable changes in recharge (Gates *et al.*, 2008c; Ma *et al.*, 2009b; Gates *et al.*, 2011; Huang and Pang, 2011).

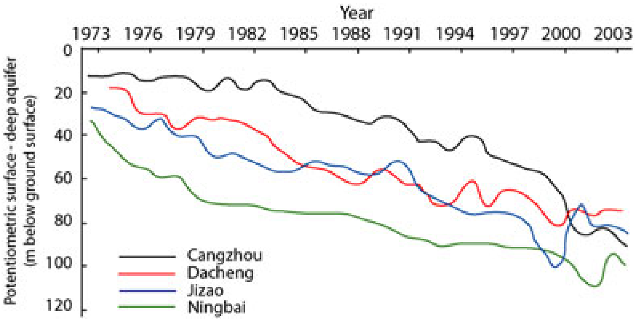

Figure 2. Typical water decline experienced in deep aquifers in northeast China (modified from Zhang *et al.*, 2009a)

Much less is known about recharge mechanisms and rates (if any) for deep aquifers in northern China. In most basins (Figure 1), the dominant natural regional recharge mechanism is thought to be leakage of streams through permeable sediments in the mountain front/piedmont of the basin margins (e.g. Foster *et al.*, 2004; Chen *et al.*, 2006b; Kreuzer *et al.*, 2009; Currell *et al.*, 2010; Ma *et al.*, 2010). Coarse sediments in these areas typically reach substantial thickness (e.g. >100 m) and comprise permeable gravels below permanent or ephemeral stream channels (which is true of the North China Plain, the Heihe Basin, Southern Gobi and Badain Jaran Deserts and Alxa Zuoqi Oases). Deep confined and semiconfined layers are probably recharged via horizontal flow in areas where these sediments grade into deep confined units away from the basin margins (e.g. Von Rohden *et al.*, 2010; Zhou *et al.*, 2011b). Although upwards fault recharge has been shown to be locally important (e.g. Yuan *et al.*, 2011), whether it is a volumetrically significant source of recharge requires further study.

An important issue relating to recharge is the effect of reservoir construction, which has impounded many major rivers in natural recharge areas. The mountain-front areas

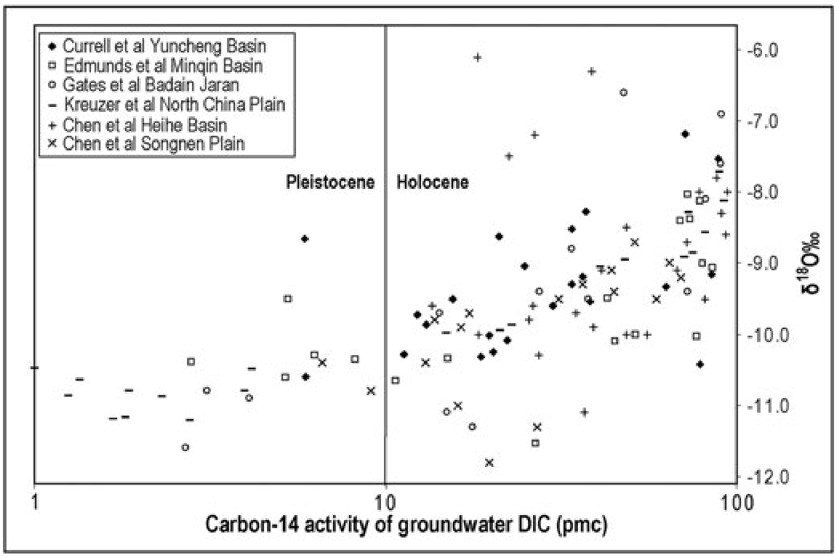

Figure 3. Groundwater radiocarbon activities and stable isotope compositions in a range of basins in northern China. Groundwater recharged during the Late Pleistocene has lower δ^{18}O and $\delta\ ^2$H contents due to recharge under cooler temperatures than the present. Data compiled from Edmunds *et al.* (2006), Chen *et al.* (2006a), Gates *et al.* (2008a), Kreuzer *et al.* (2009), Currell *et al.* (2010) and Chen *et al.* (2011)

of many basins (e.g. the Taihang Mountains bordering the North China Plain, Qilian Mountains bordering the Minqin and Heihe Basins and the Helan Mountains bordering the Alxa Oases) contain reservoirs that dam rivers that previously spread over the piedmont sediments during flooding. Reservoir construction mostly occurred between late 1950s and 1980s to capture and divert mountain runoff to supply water for urban centres (e.g. in the North China Plain) or to irrigate agriculture on the plains (e.g. in northwest China) (Foster *et al.*, 2004; Ma *et al.*, 2005; O'Dochartaigh *et al.*, 2010; Zhou *et al.*, 2011b). This has undoubtedly decreased the amount and spatial extent of surface runoff in regional recharge areas, reducing infiltration, which would ultimately feed deep regional aquifers. Particularly in arid northwest China, where rainfall is low and diffuse recharge negligible, runoff in mountain-front areas and ephemeral wadi channels represent the only substantial source of natural recharge available to deep aquifers (e.g. Foster *et al.*, 2004; Ma *et al.*, 2005; Kreuzer *et al.*, 2009; O'dochartaigh *et al.*, 2010). As an example of the effect of reservoir construction, the infiltration rate from river loss to the aquifer below the Changma alluvial fan (in the Hexi corridor) was estimated to be 0.57×10^9 m^3/a before dams were built in 1958 (58% of total runoff), although this had decreased to 0.25×10^9 m^3/a in 2004 (25% of total runoff) (Chen *et al.*, 2010). Ma *et al.* (2005) estimated that recharge via surface runoff infiltration in the mountain front of the Minqin Basin decreased by 75% between 1950s and 1990s. Another issue is the decrease in precipitation in parts of northern China observed during the last 50 years (Liu *et al.*, 2008; Zhang *et al.*, 2011), which has likely also reduced recharge rates.

Aquifer residence times and relationship to recharge. Few studies have attempted to relate regional groundwater flow velocity, total residence time (i.e. from recharge to discharge areas) and differences in historic and modern groundwater recharge rates. Because of the lack of groundwater level and pumping volume data in China, using models to simulate recharge–discharge and horizontal flow velocities is generally difficult; hence, environmental tracers (e.g. radiocarbon, chloride and tritium) are required. On the basis of the distribution of groundwater ages in most major basins, horizontal transit times from mountain-front regions to the confined layers tens or hundreds of kilometres away can be broadly estimated to be 1000 or 10 000 years (e.g. Gates *et al.*, 2008a; Kreuzer *et al.*, 2009; Currell *et al.*, 2010; Chen *et al.*, 2011). Groundwater ages in a series of wells screened at similar depths (180–200 m) in the deep semiconfined aquifer of the Yuncheng Basin show a linear increase with distance from the regional recharge area (Figures 4 and 5). This corresponds to the historic regional flow path, from the coarse alluvial fans in the mountain front near Wenxi toward the Yellow River. On the basis of the age–distance relationship, horizontal flow velocity in the deep aquifer would have been approximately 3.5 m/year, which yields a total residence time for deep groundwater (from recharge to discharge) of approximately 30 000 years. The current distribution of water levels indicates that the regional flow direction has been disturbed by pumping and that flow is now controlled by two cones of depression in areas of intensive extraction (Figure 4). The decline in potentiometric surface in the major cone of depression occurred at a rate of approximately 3 m/a between 1986 and 2000 (after which data are not available, Cao, 2005a). This compares with estimates of natural recharge through undisturbed loess in the region of approximately 30 to 100 mm/year (Lin and Wei, 2006; Gates *et al.*, 2011; Huang and Pang, 2011). Clearly, the current

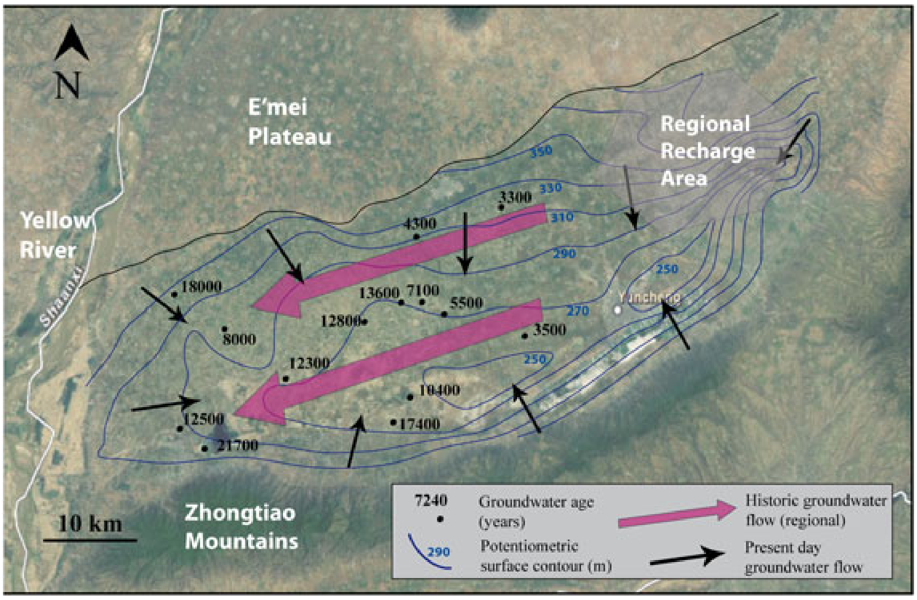

Figure 4. Example of groundwater age distribution and potentiometric surface in a regional semiconfined aquifer that has been intensively exploited in the last three decades in the Yuncheng Basin, Shanxi. Pumping has influenced the regional flow patterns and resulted in water level declines of up to 3.2 m/year (data from Currell *et al.*, 2010)

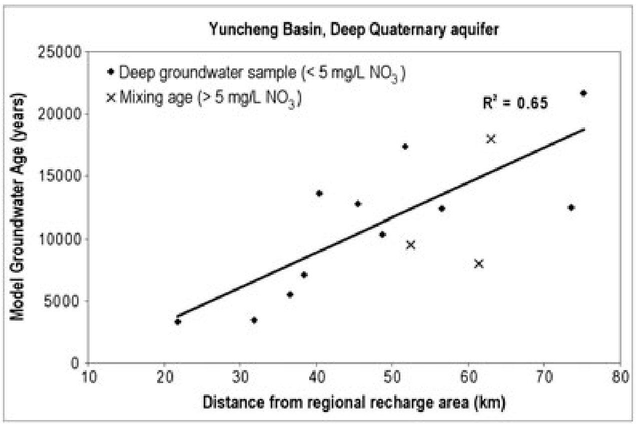

Figure 5. Model groundwater ages and distance from recharge area in the Yuncheng Basin, showing a linear increase with distance, indicating groundwater flow historically approximated horizontal piston flow with an average velocity of ~3.5 m/year before groundwater pumping

pumping rates from this aquifer are unsustainable, and the entire recharge–flow–discharge mechanism has been altered.

If radiocarbon activity can be measured in number of wells along a horizontal transect in a confined aquifer and several assumptions can be met (e.g. constant aquifer thickness, piston flow, no additional recharge via vertical leakage), then recharge rates can also be estimated on the basis of changes in tracer activity and/or model ages along flow lines (e.g. Cook and Bohlke, 2000; Herczeg and Leaney, 2011). This method was recently used to estimate recharge via horizontal flow to the confined aquifer in the Songnen Plain in northeast China, resulting in estimates ranging from 2 to 11 mm/year (Chen *et al.*, 2011). Further studies involving estimation of regional flow velocities, recharge and discharge rates and mechanisms in deep aquifers are vital for managing these large but vulnerable groundwater resources. Incorporation of data on recharge and flow rates from geochemical studies into regional groundwater models may greatly aid groundwater management (e.g. Sanford *et al.*, 2004); however, as noted, disturbance to flow regimes and lack of data for calibrating regional flow models make this challenging in most regions.

Potential mitigation strategies. To ease pressure on the palaeowaters that are exploited from deep aquifers in northern China, extraction rates must be reduced, particularly near urban centres where deep cones of depression have developed and also more broadly in agricultural areas. Land-use change (e.g. reducing areas of irrigated cropland and inclusion of fallow periods) holds potential to reduce overall aquifer depletion rates (cf. Foster *et al.*, 2004; Kendy *et al.*, 2007; Wei *et al.*, 2010); however, in the context of China's food security and agricultural policies, this is a complex issue and difficult to achieve on short timeframes (Foster *et al.*, 2004). Urban water reuse and excess runoff diversion schemes such as managed aquifer recharge (MAR) may hold potential as a way to offset the decreased recharge that has been caused by reservoir construction and reduced runoff in mountain-front areas, and the energy requirements and costs can both be relatively low (e.g. compared with water transfer and desalination) (e.g. Zhang, 1999; Foster *et al.*, 2004; Xu *et al.*, 2009). MAR could divert treated wastewater to regional recharge zones (e.g. where permeability is high and there is connection between surface infiltration and deeper aquifer layers) and could relieve pressure on aquifers downgradient. In the North China Plain, Xu *et al.* (2009) have identified seven specific regions that could be targeted for MAR, all of which are alluvial fans in the piedmont of the Taihang Mountains, where regional recharge occurs (Figure 6). The source of water diverted for recharge could be a combination of treated urban wastewater and, potentially, excess surface water (e.g. from southern China, delivered via the South to North Water Transfer Scheme) during wet years.

Groundwater quality degradation

The deterioration of quality is another major issue threatening sustainability of groundwater usage in northern China (OECD, 2007; Gleik, 2009; Han *et al.*, 2011a). In many regions, groundwater quality problems are intimately related to overuse—declining quality puts increased pressure on supplies, which further reduces quality (e.g. due to reduced dilution with fresh surface water recharge, or induced mixing of low-quality water into fresh aquifers). Groundwater provides drinking water to hundreds of millions of people in northern China; the Chinese Ministry of Water Resources reported in 2005 that approximately

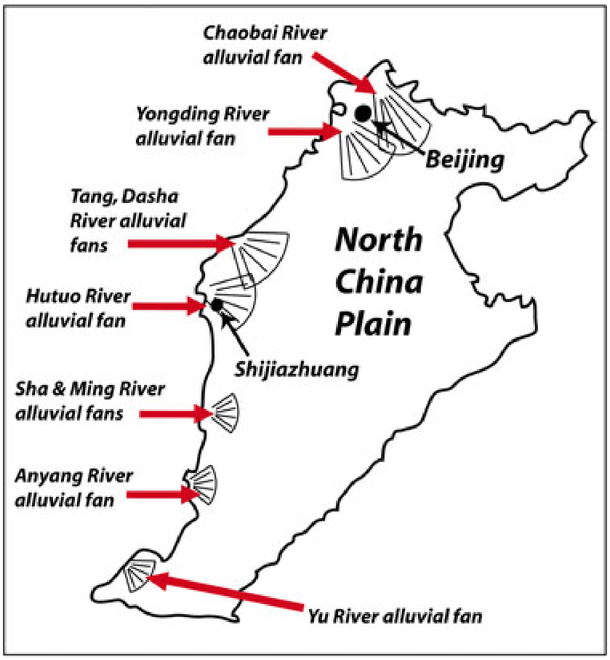

Figure 6. Locations identified as having high potential for MAR in the North China Plain. Translated and modified from Xu *et al.* (2009)

70 million people were drinking groundwater that was unsafe for human health according to World Health Organization guidelines (OECD, 2007). In many areas where domestic groundwater supplies are contaminated, there is great difficulty finding alternative water sources, as most are already heavily allocated, overused and/or polluted (Gleik, 2009). Declining quality particularly threatens not only domestic water but also, in some cases, groundwater used for agriculture. The most widespread groundwater quality issues in northern China are elevated concentrations of nitrate, fluoride, arsenic and total mineralisation (Wang and Cheng, 2001; Guo *et al*., 2003; Chen *et al*., 2005; Guo *et al*., 2007a,b; Yu *et al*., 2007; Currell *et al*., 2010; Fan *et al*., 2010; Currell *et al*., 2011), although there are many other contaminants of concern. Table II presents a summary of major aquifers where groundwater quality data have been reported, particularly focussing on these four indicators. Table II is by no means comprehensive, but it gives a broad overview of typical concentrations in the major basins. A comprehensive database of specific local water contamination problems (the China Water Pollution Map) is compiled and maintained by the Institute of Public and Environmental Affairs http://www.ipe.org.cn/En/pollution/index.aspx.

Salinisation and agricultural contamination. Groundwater quality degradation is generally most severe in shallow aquifers, where salinisation and nitrate contamination are widespread, although there is increasing evidence that these problems are also affecting deep aquifers (Currell *et al*., 2010; O'Dochartaigh *et al*., 2010). The cause of elevated nitrate and TDS contents in many cases is the change in dominant recharge source from rainfall and surface runoff to irrigation water (Hu *et al*., 2005; Chen *et al*., 2010; Currell *et al*., 2010; O'Dochartaigh *et al*., 2010). Irrigation returns are subjected to intense evapotranspiration and dissolve large amounts of N that accumulates in the soil zone from excess fertiliser application before recharging water table aquifers (Chen *et al*., 2005; Fan *et al*., 2010). Contamination in deep aquifers (when sediments are unconfined or semiconfined) occurs because of strong downward hydraulic gradients in zones of intensive exploitation and/or because of preferential pathways such as fracture and fault zones. In the Yuncheng Basin, elevated concentrations of nitrate (>20 mg/l), which are ubiquitous in shallow groundwater, now also occur in wells >200 m depth in the aquifer that contains palaeowaters with ages up to 20 ka (Currell *et al*., 2010). In the Alxa Zuoqi Oases of Inner Mongolia, groundwater in deep unconfined alluvial aquifers has experienced a steady increase in nitrate concentrations, and overall mineralisation as irrigation returns has overtaken wadi recharge as the main recharge source (O'Dochartaigh *et al*., 2010). Nitrate concentrations in the deep aquifer have reached values as high as 300 mg/l and total mineralisation as high as 6 g/l compared with nitrate and TDS concentrations of <5 mg/l and 0.4 g/l in areas outside the agricultural development. The steady increase in nitrate and total mineralisation will continue in this region, as there is a thick unsaturated zone, and hence a substantial time lag before the effects of irrigation returns infiltrating the aquifer are fully felt. In a regional study of nitrate contamination in the North China Plain, Chen *et al.* (2005) showed that elevated nitrate concentrations were concentrated in the regional recharge area at the front of the Taihang mountains and near major urban centres (e.g. Beijing and Shijiazhuang). The high NO_3 contents are due to excessive fertiliser application and irrigation with untreated wastewater (e.g. Chen *et al*., 2006b) and represent a threat to quality of the entire regional aquifer downgradient of contaminated areas.

In the arid regions of northwest China, significant changes in hydrochemistry have been observed since monitoring began. The major quality issues associated with groundwater exploitation are salinisation of shallow groundwater, soil salinity and increasing pollutant concentrations (again, particularly nitrate). Salinisation is mainly due to high water tables, where the capillary fringe intersects the depth from which direct evaporation can occur (e.g. Cui and Shao 2005). High water tables have mostly developed in northwest China because of the transfer of large amounts of surface water to artificial oases for irrigation. This has been documented in the Kalamay district of the Junggar basin (Han *et al*., 2011b), the Yanqi Basin in Xinjiang (Li, 2009), the Heihe River Basin (Chen *et al*., 2006a) and the Minqin Basin (Ma *et al*., 2005). In the Minqin Basin, Ma *et al*. (2005) estimated an increase in shallow groundwater salinity in irrigation areas of up to 2.8 g/l between 1984 and 2000 because of a combination of decreased natural fresh recharge from the Shiyang River, an infiltration of saline irrigation water and possibly an induced leakage from saline aquifer units. In 2005, it was estimated that 500 shallow wells were abandoned every year in the Minqin Basin because of salinisation. Accompanying the increased salinity, groundwater in northern China has also experienced changes in water type, with two major trends being an increase in bicarbonate concentrations and overall hardness (particularly in piedmont plain groundwater) and in other areas, a tendency towards Na-Cl-type water in areas of high salinity (Chen *et al*., 2010, Han *et al*., 2011a, Han *et al*., 2011b).

Groundwater salinity is also caused by saltwater intrusion into coastal aquifers, particularly surrounding the Bohai Sea coast. The coastal plain of Laizhou Bay (southern Bohai Sea) contains two major cones of depression relating to urban fresh groundwater extraction and brine extraction for salt production. The water level decline in these regions has occurred at approximately 0.5 m/year, which has pushed the interface between fresh and brackish water inland by approximately 6 km between 1984 and 2007 (TJR, 2006). Shallow groundwater in this area has also experienced rapid increases in nitrate concentrations, from tens of milligrams per litre in the late 1990s to hundreds of milligrams per litre (up to 350 mg/l) in 2007 because of the overuse of chemical fertilisers (D.M. Han, unpublished results; Xue *et al*., 2000). Nitrate concentrations above the natural background have recently also been observed in the deep confined aquifer (D.M. Han, unpublished results). The major urban centres Tianjin and Dalian have also experienced major saline intrusion over the last decade. The detailed salinisation mechanisms (e.g. direct seawater intrusion, brine intrusion, leakage of saline shallow water into deep units, etc.) requires further research and investigation (e.g. Han *et al*., 2011a); however it is clear that water level decline is the key driver of salinisation in coastal aquifers.

Elevated fluoride and arsenic concentrations. Elevated fluoride and arsenic concentrations in groundwater are widespread in northern China, particularly in shallow aquifers, and also in some deep, regional aquifer units (Smedley *et al*., 2003; Gao *et al*., 2007; Guo *et al*., 2007a; Guo *et al*., 2007b; Yu *et al*., 2007; Mukherjee *et al*., 2009; He *et al*., 2010; Han *et al*., 2010a; Currell *et al*., 2011). This has been identified as one of the major issues affecting water quality in arid and semiarid regions globally (United Nations, 2006). It is likely that elevated concentrations of these elements relates to natural enrichment and mobilisation from rocks and sediments, under particular geochemical conditions (e.g. Wang and Cheng, 2001; Smedley and Kinniburgh, 2002; Gao, 2005; Han *et al*., 2010b; Currell *et al*., 2011). In a systematic study of As in groundwater and coal in China, Yu *et al*. (2007) sampled more than 400 000 wells used for domestic supply and found that approximately 5% contained As concentrations of 50 µg/l or higher, and the population exposed to drinking water with toxic levels of As was estimated to be at least 500 000. Shanxi province and Inner Mongolia are the most seriously affected regions, with high percentages of wells containing water with >50 µg/l As (12.5% of 48 500 wells sampled in Shanxi) and many people suffering symptoms of arsenicosis (Yu *et al*., 2007).

Elevated groundwater fluoride concentrations (i.e. above the World Health Organization safe drinking standard of 1.5 mg/l) are extremely widespread, occurring in every province of northern China (He *et al*., 2010) and reaching levels higher than 8 mg/l in some regions (e.g. Wang and Cheng, 2001). This has caused endemic fluorosis in areas where groundwater has been used for domestic supply (Gao, 2005; Cao 2005b; Guo *et al*., 2007a). The proposed mechanism by which enrichment occurs is that fluoride is leached and transported from metamorphic rocks in mountain ranges by surface water, progressively enriched during travel from upstream to downstream areas and further increased in concentration during recharge and evapoconcentration (Wang and Cheng, 2001). Elevated groundwater F concentrations throughout northern China are also linked to particular groundwater geochemistry, notably high Na/Ca ratios, HCO_3 and pH, which suggests that limits on the amount of mineral-derived F and/or F mobilisation (e.g. due to sorption–desorption reactions with the F^- anion) are linked to local geochemical conditions (Guo *et al*., 2007a; Currell *et al*., 2011).

Need for increased monitoring. Many of the aquifers containing elevated arsenic, fluoride and nitrate concentrations have been used for domestic supply since the 1970s and 1980s. Pressure to supply domestic water and difficulty in finding alternative sources, particularly in rural China, means that millions of people have been exposed to water with high concentrations of toxic elements for extended periods (OECD, 2007; Yu *et al*., 2007). In many places, domestic wells have been abandoned as realisation that long-term use of the water has lead to arsenicosis and fluorosis. This places further pressure to find domestic water in areas with dense populations that often only have limited or heavily polluted surface water as an alternative and usually results in drilling deeper wells in an attempt to tap better quality water. The migration of contaminated water from shallow aquifers into deep layers becomes another major problem if intensive deep extraction occurs and there is potential for vertical mixing.

The main area in which future work is needed to address the issue of declining groundwater quality in northern China is monitoring and reporting of hydrochemical data. Such data are still relatively scarce and generally not publicly available (Gleik, 2009). The Institute of Public and Environmental Affairs publishes water quality data including links to water quality reports, but these largely focus on rivers. Monitoring groundwater quality, starting with the most ubiquitous indicators such as NO_3, EC and pH, is vital to determine further risks of groundwater quality and human health. Monitoring these parameters can give a rapid indication of the effects of irrigation and the spatial extent to which irrigation returns enter aquifers. Monitoring deep aquifers, particularly near faults and other preferential pathways, will help to address the issue of contamination of deep palaeowaters by polluted shallow groundwater. Monitoring F and As concentrations in groundwater used for domestic supply is vital to address the problem of chronic exposure to the toxicity of these elements. The recent joint Central Government/UNICEF programmes to target the issue of As in drinking water have resulted in strong progress in the collection and reporting of data (Yu *et al*., 2007); however, there is still generally little monitoring for fluoride and wells are usually only abandoned after populations have been exposed for long enough periods for fluorosis to be observed.

Ecological degradation and environmental health

The degradation of groundwater-dependent ecosystems is another widespread issue associated with groundwater extraction in northern China (Cui and Shao, 2005; Ma *et al*., 2005; Shen and Chen, 2010). The most serious cases of degradation are in arid regions of northwest China, where the ecosystems are marginal and sensitive to minor changes in climate, water balance and salinity (e.g. Hao *et al*., 2010; Pang *et al*., 2010). Ecosystem degradation due to groundwater extraction also occurs in the less marginal semiarid areas. In northwest China, the three related issues of soil salinity, desertification and ecosystem degradation are all strongly related to groundwater usage and irrigation practices as water and salt cycling in shallow aquifers, rivers and lakes are intimately linked (Cui and Shao 2005; Huang and Pang, 2010; Pang *et al*., 2010). The damming of rivers and the diversion of water to agricultural oases are major factors that changed the natural water balance in these regions and facilitated the spread of soil salinity and ecosystem degradation (Ma *et al*., 2005; Zhu *et al*., 2008; Shen and Chen, 2010; Han *et al*., 2011b).

An area where a large amount of research and policy effort has been directed is the Tarim River Basin in Xinjiang-Uighur autonomous region, where water shortage (largely caused by impoundment of the Tarim River in the 1960s), has led to the severe degradation of riparian vegetation (including the iconic Poplar tree and Tamarix shrub communities), the desiccation of the once massive terminal lake system (Taitema Lake) and the rapid advancement of desertification—in some cases leading to the abandonment of agricultural settlements (Shen and Chen, 2010). The clearing of native forest from the 1950s to the late 1970s reduced the resistance of topsoil to winds and increased the severity of sandstorms. The spread of desertification and ecosystem degradation led the government to institute water diversions from the Kongque River for environmental flows into the Tarim River (eight diversions of ~200 000 ML have been made since 2000) and to establish a Tarim Poplar Forest Nature Reserve in 2006. However, a major problem that remains is the loss of periodic floods to the Tarim and its tributaries. Before reservoir construction, flood water naturally spread far from the river course and recharged shallow groundwater, sustaining the desert vegetation. Since river regulation began, flood recharge to shallow aquifers has ceased. Isotopic study of tritium has shown that despite the environmental flows programme, there is still little or no modern water recharging shallow unconfined aquifers away from the main river channel (Huang and Pang, 2010, Pang *et al*., 2010).

Water table depth and ecosystem health. The key factor that controls ecosystem health in marginal arid regions (e.g. Tarim Basin, Junggar Basin, Heihe Basin and Minqin Basin) is the depth to water table. If this depth is too great, then phreatophyte vegetation is unable to reach water, and the soil moisture is inadequate to sustain nonphreatophyte vegetation (Cui and Shao, 2005; Hao *et al*., 2010). However, if the water table is too shallow, water logging occurs and soil salinity and/or shallow groundwater salinisation occur (e.g. Han *et al*., 2011b). Several recent studies have focussed on estimating optimum water table depths for sustaining vegetation in northwest China (e.g. Xie and Yuan, 2010). Hao *et al.* (2010) modelled the relationship between species diversity and water table depth in several experimental plots in the Tarim Basin and found that the optimum depth was between 2 and 4 m, with the maximum threshold depth for vegetation survival at 6 m. Cui and Shao (2005) performed similar analyses in the Tarim and Manas River Basins and estimated optimum water table depths in the same range (2–4 m), although they noted that the depth is highly dependent on soil type and that a better measure of site-specific threshold is approximately one capillary height thickness below the zero-flux plane for the specific soil. Maintaining optimum water table depths in these large arid areas is a major challenge. River regulation and diversions have both reduced groundwater recharge in mountain-front areas (as discussed earlier) and flood water that sustains riparian vegetation and also contributes to rising water tables and salinity in heavily irrigated oasis settlements (Ma *et al*., 2005; O'Dochartaigh *et al*., 2010; Han *et al*., 2011b). Water management strategies must therefore include a whole water balance approach, with the maintenance of favourable water table depths throughout basins a forefront consideration.

Lake and wetland ecosystem water balance. Lake systems are also highly sensitive to groundwater levels and recharge–discharge regime. The Tengger Desert and Badain Jaran Desert in the Gansu/Inner Mongolia region contain unique groundwater-dependent ecosystems, which occur in several chains of groundwater-fed lakes. These lakes support grassland/meadow communities and aquatic ecosystems, provide drinking water for camels and support eco-tourism. The lakes are entirely groundwater fed and form within topographic depressions between mega-dunes, which reach up to 500 m height (Chen *et al*., 2004; Ma and Edmunds, 2006; Ma *et al*., 2009b). Lake level and salinity are controlled by the interplay between groundwater inflow and outflow, lake surface area-to-volume ratio and evaporation rates. The salinity stratification pattern indicates that some lakes are fed by artesian groundwater flow from beneath, and the occurrence of fresh springs and seeps around the margins of otherwise saline lakes indicates that they are also supported by intersection of the dune topography and shallow phreatic fresh groundwater (Ma and Edmunds, 2006; D.C. Bradley, unpublished results). Isotope/geochemical studies by Ma and Edmunds (2006) and Gates *et al.* (2008a) indicate that the lakes (like the deep confined groundwater reserves in these areas) are sustained by palaeowater, recharged thousands of years before present, and that modern recharge (e.g. via diffuse rainfall) is negligible. Hence, these are fragile systems that greatly depend on local water balance. Although these areas are sparsely populated, and significant groundwater resource development is unlikely, a recent study of satellite data indicates that the lakes have warmed significantly since 1985 (Schneider and Hook, 2010), which may in itself threaten the viability of these marginal eco-environments. Likewise, any upgradient groundwater usage or reduction in recharge threatens these systems.

Similar issues affect northeast China where the climate is less marginal but the population and water resource exploitation more intensive, such as the Baiyangdian wetland system in Hebei province. This wetland system originally comprised 143 sublakes, with a combined surface area of approximately 1000 km^2, which has now shrunk to less than 400 km^2, and suffers periods of complete dryout (Moiwo *et al*., 2010). The wetlands are naturally fed both by runoff (from several river tributaries) and by groundwater discharge; however, reservoir construction and groundwater level depletion have starved the lake of inflows over recent years, whereas discharge of urban wastewater and aquaculture have also caused significant water quality degradation (Xu *et al*., 2011; Zhuang *et al*., 2011). This led the Chinese Government to seek the assistance of the Asian Development Bank to carry out the Baiyangdian Lake Project, aimed at preserving/restoring the wetlands using integrated water resource management (Asian Development Bank, 2007). One of the key findings of the programme is that groundwater level decline and alteration of the recharge/discharge regime (in addition to impacts from surface flows) are major factors that must be considered in the integrated management (Moiwo *et al*., 2010).

Further research is needed to more completely understand the degree of dependence of arid and semiarid ecosystems on groundwater and the required ranges of water quality and quantity characteristics (e.g. water table depth, groundwater salinity) needed to sustain them. Management needs to focus on the full water cycle and manage catchments and groundwater basins with an objective of maximising the area over which optimum water table depths and water quality can be sustained. Further research is needed to better understand the role of palaeowater (as opposed to modern, cyclic recharge) in supporting groundwater-dependent ecosystems and in maintaining flows to surface water bodies. Further isotopic and age dating studies of groundwater used by ecosystems and better characterisation of groundwater–surface water interaction in lakes and rivers is an important component of this research (e.g. Ma and Edmunds, 2006; Gates *et al*., 2008a).

DISCUSSION: CURRENT STRATEGIES, FUTURE CHALLENGES AND REASONS FOR OPTIMISM

Direct domestic water usage is increasing in northern China, as is indirect and induced water use—particularly due to increased levels of urbanisation and energy consumption (predominantly supplied by coal production), which requires a large amount of water (Cai, 2008; Zhu *et al*., 2009; Schneider and Ivanova, 2011). Energy production is projected to use 188 billion m^3/year (28% of China's total water usage) by 2020, and agricultural water use is predicted to peak and decrease to 54% as a proportion of total usage (from 62% at present) (Schneider, 2011). Current strategies to address the water shortage in northern China mostly focus on large engineering projects, such as water transfer and desalination (Zhang *et al*., 2009c; Watts, 2011). These schemes offer potential to supply water but are also very energy intensive.

The South–North Water Transfer Project will deliver an extra approximately 35 billion m^3 of water per year to northeast, north-central and (possibly) northwest China, beginning in 2014 (Jaffe and Schneider 2011). This represents a major opportunity to alleviate pressure on northern China's stressed groundwater resources. In Beijing, it is proposed that the city's 40 000 private groundwater wells will be phased out of use once water from the transfer arrives (People's Daily, 2011). However, even with the extra water delivered from the south, Beijing alone is still projected to experience a total water shortage of 190 million m^3 per year and require further water transfers from the already stressed Yellow River system (Yan, 2011). Hence, in many cases, the South–North transfer water has already been allocated before it has arrived (Ivanova 2011). Using water balance estimation techniques, Zhang *et al*. (2009c) analysed the deficit between groundwater extraction and replenishment in the North China Plain and predicted that even with the additional water from the transfer arriving in 2014, there would still be a water deficit of 2.1 billion m^3 per year over the Plain in 2020, and hence the aquifers will continue to be overexploited. As discussed earlier, MAR using wastewater (Bouwer, 2002; Dillon, 2005; Dillon *et al*., 2008) may provide an alternative small-scale, low-cost option that could alleviate the pressure on many local aquifers in northern China, addressing the reduction in recharge that has been caused by reservoir construction in mountain-front areas (Xu *et al*., 2009). Other similar water reuse and recycling schemes accompanying China's rapid urbanisation offer potential to ease groundwater declines and even reduce intersector water conflicts (Kendy *et al*., 2007).

Many local initiatives have recently been developed, which are helping to improve water efficiency and raise awareness of water quality issues in rural and urban areas. For example, academics at China Agricultural University provide free education workshops to farmers in the North China Plain to improve their understanding of problems associated with water and fertiliser overuse and to suggest ways to farm more efficiently. A huge research effort has been carried out in recent years toward optimising farming techniques with respect to water and fertiliser (Fang *et al*., 2010). Progress in improving water use efficiency is occurring in several northern Chinese provinces, with the aid of World Bank and Chinese government funding assistance. An example is the Ningxia autonomous region, where agricultural water usage has greatly improved and farmers have increased yields while reducing water use by 30% (Schneider, 2011). This was forced by a cap that limits withdrawals permitted from the Yellow River in Ningxia and other provinces in the catchment's headwaters. The energy industry and local government both provided funds to modernise irrigation distribution networks and reduce water losses, allowing efficiency to improve. According to the Ministry of Water Resources, China is prepared to invest $US60 billion (RMB 400 billion) over the next decade in irrigation infrastructure upgrades and other water production and transport measures.

In the Heihe River basin, ecological restoration activities have been implemented since the late 1990s under the 'Gansu-Inner Mongolia Water Allocation Plan', including releases of environmental water to starved ecosystems and restrictions on irrigation withdrawals. This has led to improvements in irrigation efficiency via changes in land use and uptake of water-efficient technologies that are subsidised by central government funding (Liu *et al.*, 2005; Cai 2008). Some ecological restoration of riparian vegetation has also been achieved because of the water diversion programme mentioned earlier in the Tarim Basin (e.g. Sun *et al.*, 2011). These examples show that provided the right policy and funding incentives are in place, improvements in water efficiency can occur rapidly.

Several recent programmes are also targeted at addressing the issue of water quality. The China Arsenic Mitigation Network was established in 2001 (Yu *et al.*, 2007) and has continued through 2006 to 2011, involving both monitoring and finding methods to address the issue of chronic exposure to arsenic from groundwater and other sources. However, more regular and widespread monitoring and reporting of other groundwater quality data (e.g. F, NO_3, TDS) is vital if the issue is to be addressed substantially. The most recent government 5-year plan includes targets to reduce water pollution and substantial investment in wastewater treatment; however, much of the policy is still targeted at surface water. The links between water use, agriculture and industrial activities and water quality must be more clearly understood and incorporated into policy, considering the full water cycle and its relationship to human and environmental health.

CONCLUSIONS

As China moves toward increasing levels of urbanisation and energy and water demand increase, water supply and quality problems are intensifying, and great pressure is being exerted on groundwater in the arid and semiarid regions of the north. Several major issues have been highlighted in this review:

1. There is an unsustainable dependence on palaeowaters extracted from deep aquifers in northern China.
2. Current recharge rates and mechanisms to deep aquifers are poorly constrained, but it is unlikely there is significant recharge occurring at present, and there is a massive deficit between extraction and replenishment.
3. Recharge to unconfined aquifers is occurring at variable rates (<4 mm/year in northwest China to ~1 m/year in parts of the North China Plain).
4. Groundwater quality in shallow and deep aquifers is declining as irrigation leakage has taken over from surface runoff as the dominant recharge mechanism to phreatic groundwater.
5. Vertical leakage into deep aquifers that are not fully confined and saline intrusion have the potential to further degrade the quality of deep palaeowaters.
6. Groundwater extraction, surface water diversion and irrigation practices have caused serious degradation of northern China's groundwater and ecosystem health, and this will continue until major initiatives are taken to restore healthy water and solute balances.

These issues present enormous challenges for water management in northern China. As shown in this review, there is a very strong connection between shallow aquifers, deep aquifers and surface water, and actions that affect one of these storages tend to have flow-on effects (both quality and quantity) on the other storages. Returning to situation of sustainable groundwater usage will require a full assessment of the water cycle and a combination of as many measures that can conserve water and improve/protect its quality as possible, including

- increase in water use efficiency in the agricultural, municipal and industrial sectors;
- reductions in groundwater pumping, particularly deep pumping near urban centres where major cones of depression exist and in agricultural basins where high quality deep groundwater is at risk from vertical leakage of poor quality shallow water;
- groundwater level monitoring to aid the assessment of areas where pumping and/or irrigation may require restriction to prevent quantity and quality problems;
- increase in monitoring and reporting groundwater quality data and enforcing controls on polluting activities;
- reductions in fertiliser usage and excess nitrate accumulation from farming;
- technological solutions, such as water recycling, irrigation infrastructure modernisation and MAR, along with the major engineering projects currently under construction (e.g. the South–North Water Transfer Project and desalination);
- participation and communication between public, industry and government.

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