Quaternary Aquifer of the North China Plain—assessing and achieving groundwater resource sustainability

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Abstract The Quaternary Aquifer of the North China Plain is one of the world's largest aquifer systems and supports an enormous exploitation of groundwater, which has reaped large socio-economic benefits in terms of grain production, farming employment and rural poverty alleviation, together with urban and industrial water-supply provision. Both population and economic activity have grown markedly in the past 25 years. Much of this has been heavily dependent upon groundwater resource development, which has encountered increasing difficulties in recent years primarily as a result of aquifer depletion and related phenomena. This paper focuses upon the hydrogeologic and socio-economic diagnosis of these groundwater resource issues, and identifies strategies to improve groundwater resource sustainability.

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Résumé L'aquifère Quaternaire de la Plaine du Nord de la Chine est l'un des plus grands systèmes aquifères du monde; il permet une exploitation énorme d'eau souterraine, qui a permis des très importants bénéfices socio-économiques en terme de production de céréales, d'emplois ruraux et de réduction de la pauvreté rurale, en même temps que l'approvisionnement en eau potable et pour l'industrie. La population comme l'activité économique ont remarquablement augmenté au cours de ces 25 dernières années. Elles ont été sous la forte dépendance du développement de la ressource en eau souterraine, qui a rencontré des difficultés croissantes ces dernières années, du fait du rabattement de l'aquifère et des phénomènes associés. Cet article est consacré aux diagnostiques hydrogéologique et socio-économique des retombées de cette ressource en eau souterraine; il identifie les stratégies pour améliorer la pérennité des ressources en eau souterraine.

Resumen El acuífero cuaternario de la Llanura Septentrional de China es uno de los mayores sistemas acuíferos del mundo y soporta una enorme explotación de su agua subterránea, las cuales han originado grandes beneficios socioeconómicos en términos de producción de grano, empleo en agricultura y mitigación de la pobreza rural, además de proveer agua para abastecimiento urbano e industria. Tanto la población como la actividad económica han crecido mucho en los últimos 25 años con una gran dependencia de las aguas subterráneas, que ha encontrado dificultades recientes por la explotación intensiva del acuífero y fenómenos relacionados. Este artículo se centra en la diagnosis hidrogeológica y socioeconómica de los problemas relacionados con las aguas subterráneas e identifica estrategias para mejorar la sustentabilidad de este recurco.

Introduction

Importance of Groundwater Resources

A Quaternary aquifer occupies extensive tracts of the Hai River basin, and of the catchments of the adjacent Huai and Huang (Yellow) river systems and beyond. This large area is amongst the most densely inhabited and most developed parts of China, and comprises a number of extensive plains (known collectively as the North China

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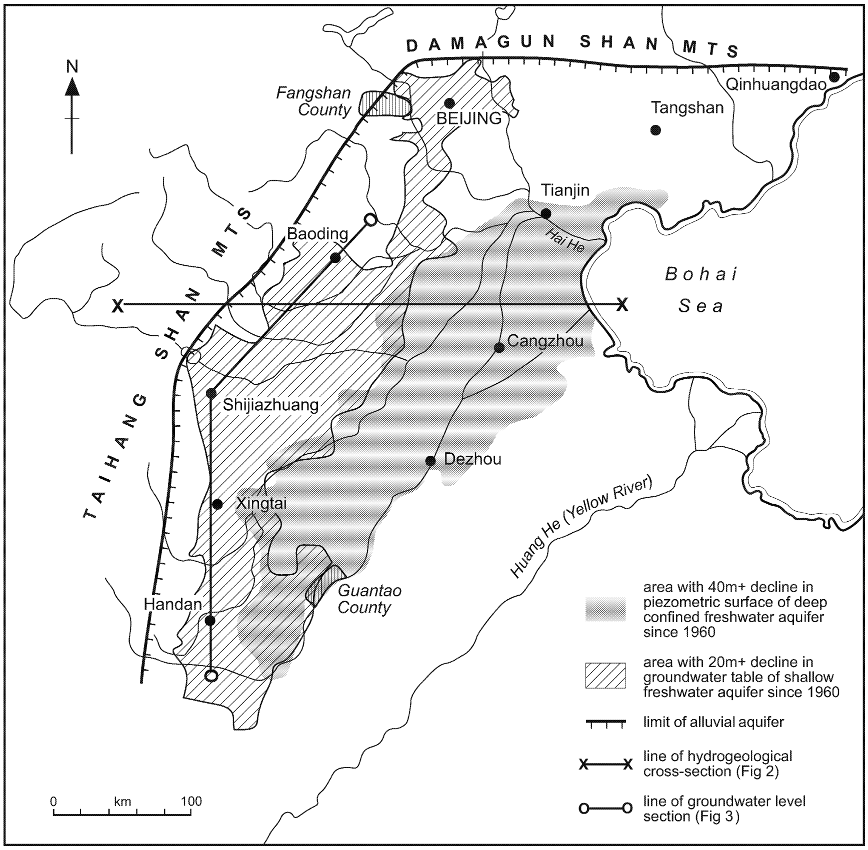

Fig. 1 Sketch map of the North China Plain showing the distribution of areas exhibiting marked aquifer depletion (based on data provided by the Ministry of Geology and Mineral Resources/Ministry of Land Resources, MGMR/MLR)

Plain). This paper relates primarily to the Hai River basin, including Beijing and Tianjin municipalities together with most of Hebei and small parts of Shangdong and Henan provinces. The area has a total population in excess of 200 million and is both the predominant national centre of wheat and maize production (Crook 1999) and an extremely important industrial region.

Both population and economic activity have grown markedly in the past 25 years, and much of this development has been heavily dependent upon groundwater resources. An estimated water supply of 27,000 Mm^3/year (Mm^3=one million cubic meters) in the Hai He basin was derived from wells and boreholes in 1988 (MWR 1992). This enormous exploitation of groundwater has reaped large socio-economic benefits, in terms of grain production, farming employment, poverty alleviation, potable and industrial water supply, but it has encountered increasing difficulties (Fig. 1) in the past 10 years or so (Hai River Basin Resources Commission 1997; Yellow River Basin Resources Commission 1997).

Prevailing Hydrogeological Conditions

This semi-arid area of north-eastern China is characterised by cold, dry winters (December–March) and hot, humid summers (July–September), and comprises three very distinct hydrogeological settings within the Quaternary aquifer system (Institute of Hydrogeology & Engineering Geology 1979; Evans and Han 1999) (Fig. 2):

- the gently sloping piedmont plain and associated major alluvial fans,
- the main alluvial plain (Heilongang), with many abandoned channels of the Hai River and its tributaries, and the lower Huai and lower Huang rivers (the silted bed of the latter now actually forming the water-divide between the Hai and Huai drainage systems), and
- the coastal plain strip around the margin of the Bohai Sea.

The following general observations can be made about the hydrogeology of the complex Quaternary aquifer system of the North China Plain (Figs. 1 and 2), and which are relevant to the evaluation of its groundwater resources:

- hydraulic conductivity (permeability) and specific yield (storativity) increase in the direction of the escarpment bounding the aquifer system to the west and north,
- the subsurface infiltration capacity and natural recharge rates (from excess rainfall and river flow) also tend to increase in the same direction,
- at some distance from the escarpment, sufficiently consistent and thick aquitards are present to separate the aquifer into layers, with the groundwater of the

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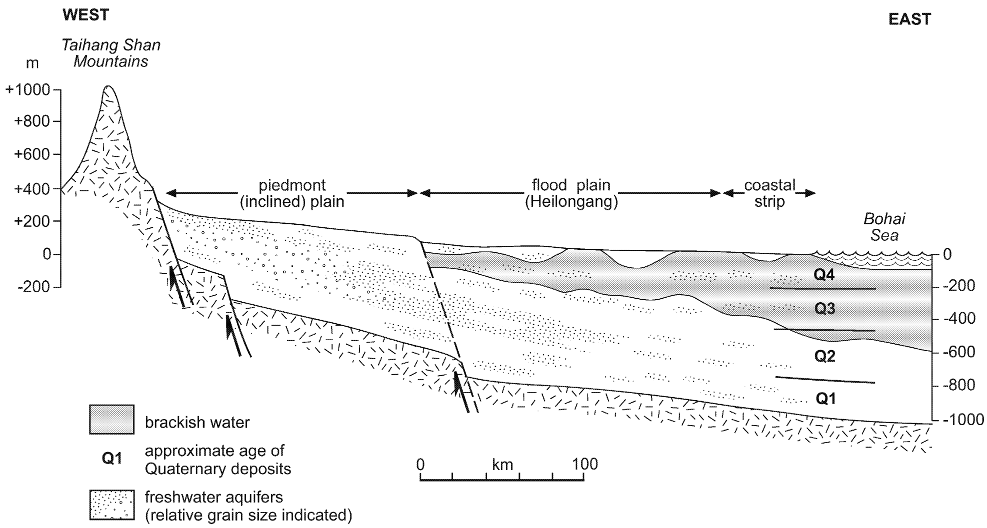
Fig. 2 Cross section of the North China Plain showing the general hydrogeological structure



deeper fresh-water aquifer demonstrating hydraulically-confined behaviour,

- below most of the Heilongang and coastal strip, the sequence includes an overlying brackish-water aquifer of large geographical extension, and the latter area may also have localised intrusions of more recent and/or modern seawater (Xue et al. 2000),
- this brackish-water aquifer is locally overlain by thin lenses of fresher groundwater, associated with existing and historic surface-water channels and major irrigation canals.

Identification of Resource Issues

The principal concerns over the status of groundwater resources in north-eastern China fall mainly into the following key issues:

- the falling groundwater table in the shallow fresh-water aquifer,
- declining groundwater levels in the deep fresh-water aquifer,
- aquifer salinisation as a result of inadequately controlled pumping (Evans and Han 1999), and
- aquifer pollution from uncontrolled urban and industrial wastewater discharge (Foster and Lawrence 1995).

These issues are to some degree interlinked but do not affect the three main hydrogeological settings equally (Table 1) and, to advance their discussion, it is essential to make a clear distinction in this regard. The objective of this paper is to concentrate upon the diagnosis and mitigation of these issues (Table 2). However, it is

Table 2 Summary of main mitigation options for groundwater resource depletion on the North China Plain

Option	Groundwater resource depletion	
	Shallow aquifer	Deep aquifer
Agricultural water savings	+++[a]	++
Agriculture crop changes[b]	++	++
Partial ban on cereal crop irrigation	++	+++
Urban and industrial water savings	++	+++
Aquifer artificial recharge[c]	++	o
Utilisation of wastewater[d]	++	o
Utilisation of brackish water[e]	o	+

[a] +++, major potential; ++, good potential; +, minor potential; o, not important
[b] Only currently viable near to major cities where market exists
[c] In many instances will need more reliable source of surface water than major flood events and this will require surface engineering measures
[d] Requires pilot schemes to adapt techniques to local conditions
[e] Needs experimental sites to develop techniques

Table 1 Key groundwater issues on the North China plain according to hydrogeological setting

Issue	Hydrogeological setting		
	Piedmont plain	Flood plain	Coastal plain
Falling water-table of shallow fresh-water aquifer	+++[a]	+++	+
Depletion of deep fresh-water aquifer	o[b]	+++	++
Risk of shallow aquifer and/or soil salinisation	o	++	+++
Groundwater pollution from urban and industrial wastewater	+++	+	o

[a] +++, very important; ++, important; +, minor importance; o, not important
[b] Effects of excessive abstraction may be reflected in overlying shallow freshwater aquifer which is here in hydraulic continuity

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Table 3 Institutional evolution of groundwater management in China

–1979	1980–1997	1998–2001	2002–
Collective management: tube wells operated by village leaders	*Private ownership and management*: tube wells and other facilities increasingly shifting from collective to individual management under 'reform of ownership of small, rural water resources facilities'		
Rural groundwater management under Ministry of Water Resources (MWR)			*Integrated groundwater management* under Water Resources Bureaux, following local government restructuring and promulgation of 2002 Water Law
Urban groundwater management under Ministry of Construction		*Urban Groundwater Management* under MWR, following central government reform	
Groundwater monitoring under MGMR/MLR and MWR			
Hydrogeological information under Ministry of Geology and Mineral Resources (MGMR), now Ministry of Land Resources (MLR)			

recognised that an integrated approach, including consideration of upstream surface-water utilisation and management in the Huang River basin in particular, is required for full resolution of some of the problems.

Groundwater Management Arrangements

Water resources management in China has evolved over the past 25 years hand-in-hand with political and institutional change (Table 3). In particular, groundwater management has gone from highly fragmented to become more institutionally integrated and decentralised, with specific roles being assigned to each level of government and more active stakeholder participation at all levels.

In actual fact, day-to-day groundwater administration is carried out mainly at the local level by Water Resources Bureaux (WRBs), normally designated at County level, except in urban municipalities where the equivalent is the District. This highly decentralised (and, in effect, 'bottom-up') approach is potentially a major asset, since it presents opportunity for close interaction between the responsible agency and the users (and potential polluters) of the resource.

The institutional groundwater management flowchart (Table 4) summarises responsibilities from the national level (State Council) down to the township level. Water resources and all water-related activities are usually managed by the WRBs for the corresponding administrative jurisdiction, and only those issues going beyond the given jurisdiction or having transboundary impacts are taken care of by the next level up. The solid arrows in Table 4 depict such political dependency, while the broken arrows indicate indirect leadership—mainly professional guidance from higher-level authorities without any hierarchical subordination. County governments have the power to issue groundwater regulations for the aquifers within the county boundaries, provided they are consistent with provincial and national regulations.

The fact that some Water User Associations (WUAs) for irrigated agriculture (albeit mainly for surface water) have also been established recognises that water resource administration cannot be achieved without user participation, and this is especially the case for groundwater policy making and for water-well abstraction permit administration.

However, there are still various factors impeding effective groundwater resource management:

- different government departments are concerned only that their individual targets for development and production are met, regardless of the consequences for groundwater resources (thus, a higher priority is generally placed on short-term agricultural productivity than longer-term water resource sustainability),
- by the same token, government departments related to urban development and those dealing with rural issues lack coordination with regards to groundwater management,
- the 'common pool' nature of groundwater requires that a mechanism for broader participation be established, including representation of urban and industrial users in addition to the (irrigation) WUAs,
- in many counties the issuing of groundwater abstraction permits is proceeding only slowly, despite the permit requirement having been introduced in 1993 and comprehensive water-well registers having already been drawn-up in most cases,
- lack of a consistent link between groundwater resource estimates and authorised abstraction rates on permits, even in areas subject to marked aquifer depletion,
- the absence of a fully-fledged groundwater rights system (Garduño 2001) makes it difficult to enforce water savings universally, and results in individual conscientious users having little motivation to save water,
- groundwater resource administration is widely regarded as merely 'clerical work', rather than a complex, multi-facetted social task for which close relationships between technical and administrative personnel are needed to promote more effective aquifer management,
- abstraction permits are usually handled manually, but appropriate computerised databases would facilitate administration, and improved filing and secure storage are required to safeguard records in view of their legal significance,
- to date local Environmental Protection Bureaus (EPBs) at county/district level have been largely ineffective in regulating discharge standards for urban and industrial wastewater.

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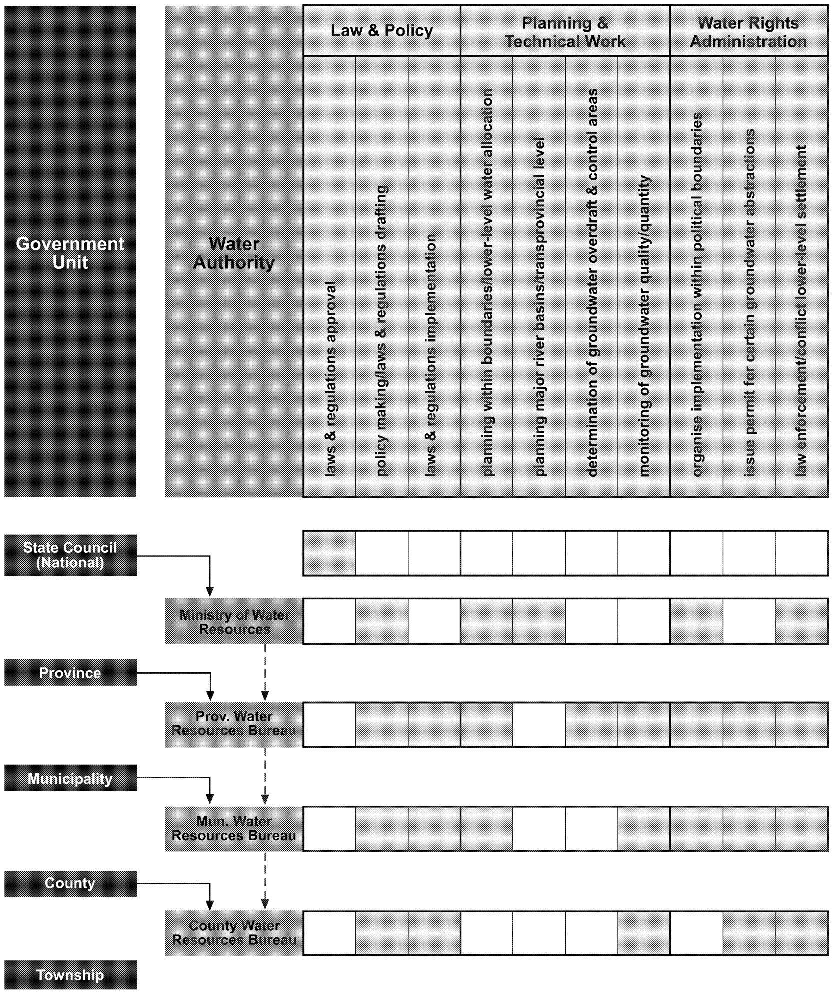
Table 4 Roles of groundwater authorities at different political levels



While practical groundwater management is clearly best performed at county level, provincial or municipal government should have a clearer role, including:

– coordinating the management of resources shared by several counties within their jurisdiction, and
– promoting training programmes in resource management, including the sharing of experiences between counties.

Currently the responsibilities of River Basin Commissions (RBCs) in groundwater resource management are also not clearly defined. They could play an important role in establishing and enforcing (under the direction of the Ministry of Water Resources, MWR) more effective and integrated use of surface water, groundwater and wastewater resources between provinces or municipalities, using the leverage of financial allocations.

Status of Groundwater Resource Degradation

Diagnosis of Falling Water-Table in the Shallow Aquifer

Over most rural areas on the piedmont plain, and stretching onto the alluvial flood plain, the shallow aquifer has experienced a water-table decline of more than 20 m over the past 30 years (Evans and Han 1999; China Institute of Geosciences 2000) (Fig. 1). Much greater declines have been observed in most urban centres (Han 1997) (Fig. 3). For example, over an extensive area around Shijiazhuang the water-table fell at an average rate of more than 1 m/year during the period 1965–1995, as the result of the abstraction of some 1,270 Ml/day from over 600 water wells, 65% of which were for industrial self-supply (Ml=one million litres).

While significant (and in some cases delayed) lowering of the groundwater levels is often necessary for major groundwater development (Foster et al. 2000), it has been independently estimated for the Hai River basin in 1988 that average groundwater abstraction exceeded recharge by some 8,800 Mm^3/year (MWR 1992). Using what is considered to be a reasonable range of values for specific yield of the strata drained (increasing westwards from

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Fig. 3 Historical evolution of the water-table of the shallow aquifer along a north–south transect of the North China Plain (based on data provided by the MWR)

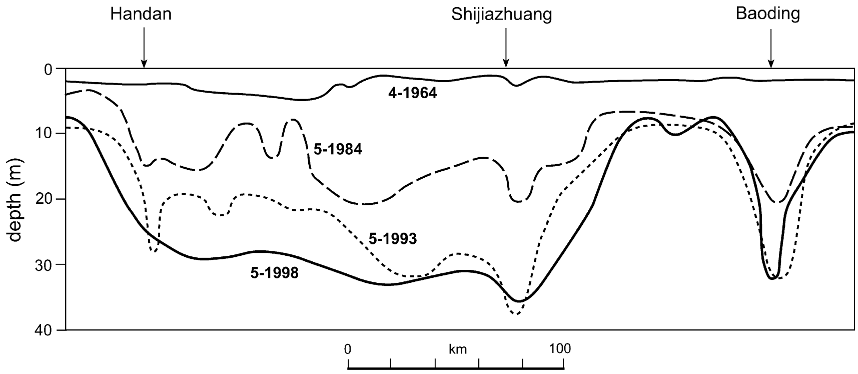

Table 5 Simplified local water balance for typical present cultivation regime on the North China Plain

Parameter	Average values (mm/year)	
	Northern parts	Southern parts
Local water availability (rainfall and snowfall)	620	560
Crop water demand (100%SM+70%WW)	700	700
Evapotranspiration—summer maize (SM)[a]	(460)	(460)
Evapotranspiration—winter wheat (WW)[a]	(340)	(340)
Deficit of crop demand–local availability[b]	80	140

[a] Includes estimate of crop-beneficial and non-beneficial evapotranspiration for current cultivation regime, but assumes zero evaporation from fallow fields and other land uses
[b] Assumes no surface water inflow/irrigation nor regional groundwater inflow from alluvial fans/mountain escarpment, and no surface runoff from the local area concerned

0.08 to 0.18), the continuous long-term water-table decline of 0.5 m/year equates to an average recharge deficit of 40–90 mm/year.

It is instructive to compare this estimate of aquifer recharge deficit with estimates derived from county-level water-balance calculation based on crop water requirements in relation to annual rainfall (Shen and Wang 1999), bearing in mind that at present about 70% of the land is cultivated with groundwater-irrigated winter wheat (Table 5). Such simple water balances do not take all factors adequately into account, and numerical aquifer models are required (and being developed) to evaluate the groundwater resource situation in more detail. Nevertheless, it is evident that:

– the possibility of significant groundwater inflow from upstream (reducing the deficit indicated) decreases markedly with increasing distance from the mountain escarpment and alluvial fans,
– the assumption of no surface-water inflow and irrigation in the county area under consideration (which could also have reduced the deficit) is now realistic for extensive areas (but not all) of the plain, because many of the rivers issuing from the neighbouring mountain escarpment have been impounded and much of their runoff diverted for urban water supply,
– the deficit may be higher than indicated for much of the flood plain area, since here a proportion of the local annual rainfall generates surface runoff,
– the residual deficit (after taking account of all of the above factors) is currently being made-up by depletion of aquifer storage reserves.

However, it has also become increasingly difficult to distinguish the effects of groundwater abstraction for agricultural irrigation from those of other pumping, because of the rapid growth of innumerable small towns heavily dependent on groundwater supply.

On the Heilongang (an area with average rainfall below 550 mm/year), problems of falling water-table in the phreatic aquifer are less marked (Fig. 3), primarily because of limited aquifer potential due to thin and patchy development (Evans and Han 1999). But water-table depletion has coincidentally reduced the problem of soil salinisation, although this extensive area is still one which is characterized by the presence of brackish water at relatively shallow depth.

It is of interest to consider what would be the preferred water-table depth from the agricultural standpoint (avoiding land drainage, soil freezing and salinisation problems, maximising groundwater recharge and minimising energy pumping costs). A minimum depth of 5 m below ground level (b.g.l.) and a maximum of 1 m b.g.l. at the onset and end of the wet season (June and October) respectively is estimated to be optimum, bearing in mind that up to 550 mm can fall in 4 months (with maximum intensities exceeding 100 mm/day), and that the land surface is extremely flat and without micro-relief. However, it is extremely unlikely that water-table recovery to this level is achievable.

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Table 6 Estimation of potential agro-economic impact of eventual loss of irrigation using non-renewable groundwater reserves

Factor	Estimate
Current area under cereal cultivation within groundwater resource depletion zone	5.0×10^6 ha
Proportion of area with irrigated winter wheat	70%
Present average winter wheat yield	4,000 kg/ha
Typical unit value of winter wheat	US $ 120/metric ton[a]
Probable crop reduction resulting from irrigation water loss	50%
Value of agricultural production at risk from unsustainable groundwater abstraction	US $ 840 million/year[a]

[a] For Chinese yen (CY), multiply by 8

Economic Significance of Groundwater Sustainability

The major consumptive use of groundwater on the North China Plain is currently the irrigation of cereal crops, for which a cropping intensity of about 1.7 is achieved with a combination of (regularly irrigated) winter wheat and (occasionally irrigated) summer maize.

It is of relevance to estimate the significance of the recharge deficit of 40–90 mm/year in terms of the proportion of cereal cropping dependent upon mining non-renewable groundwater storage reserves, bearing in mind that it requires some 1,000 m^3 of water to produce 1 metric ton (t) of grain. A preliminary estimate using the limited available data and making various assumptions is given in Table 6. The average yield of winter wheat has increased from less than 1,000 kg/ha in the 1950s to more than 4,000 kg/ha in the 1990s, as a result of irrigation with groundwater, improved crop strains, better cultivation techniques, and the use of agrochemicals. But if groundwater availability for irrigation was restricted to current average recharge, yields could reduce by as much as 50% in a growing season of average rainfall (and more in dry years), and the agricultural production at risk from unsustainable groundwater abstraction is thus estimated to be around 7.0×10^6 t/year, valued at some US $ 840 (C Y 6,720) million/year (C Y=Chinese yen) (Table 6).

The accuracy of this estimate is open to question, since direct groundwater recharge from rainfall on the piedmont plain averages some 50 mm/year, and this would continue to be available. Although this renewable resource would only support one or two (as opposed to three) applications per crop, such ‘deficit irrigation’ would still allow the possibility of providing supplemental water at critical crop growing periods, and thereby limiting yield reductions.

The cropping of summer maize (with current yields of around 5,000 kg/ha and a market value of US $ 110 (C Y 880)/t) is far less dependent upon groundwater, but reduced availability for irrigation would also have a substantial impact on production in drought years.

The question also arises of how much further could the water-table of the shallow fresh-water aquifer fall before it becomes totally uneconomic for farmers to irrigate cereal crops, assuming no other serious side-effects (such as irreversible aquifer deterioration and environmental impacts) occur earlier. It is evident that with a water-table depth of around 50 m b.g.l. (and irrigation energy costs of more than US $ 20 (C Y 160)/ ha per lamina), farmers are reducing from three (or more) to two irrigation applications and beginning to seek water-saving measures.

Assessment of Deep Freshwater Aquifer Depletion

The entire plain is underlain by a deep fresh-water aquifer of very low salinity and apparently excellent quality (except for the occurrence of excessive fluoride content for potable supply in some places). The groundwater in this aquifer exhibits a confined hydraulic condition and occurs beneath an intermediate, brackish-water aquifer across much of the Heilongang and coastal plain (Fig. 2), reaching to at least −400 m mean sea level (m.s.l.), well below the Bohai seafloor at around −30 m m.s.l.

In recent decades the aquifer has been rapidly developed for urban and industrial water supply, and in some areas (where the shallow fresh-water aquifer is thin or absent) for agricultural irrigation. Distant from the escarpment this has led to rapid decline in the piezometric surface of its groundwater (Evans and Han 1999) (Fig. 1), with serious land subsidence and salinisation at some locations (Lin and Shu 1992).

In the Cangzhou urban area, abstraction of around 200 Mm^3/year has produced a water-level decline of around 5 m/year, and detailed hydrogeological investigations have suggested a major revision of earlier estimates of replenishable resources (from over 500 Mm^3/year to below 50 Mm^3/year) is necessary. In the Tianjin urban area excessive abstraction of deep groundwater historically caused land subsidence of up to 3.0 m (Foster et al. 1997).

There is a definite question of whether any significant fresh-water replenishment is reaching the down-dip parts of the deep confined aquifer, and a serious risk that inflow of saline water will be induced from the overlying brackish-water aquifer (Fig. 2), if the piezometric surface is heavily drawn-down.

The main recharge area of the overall aquifer system is found on the upper parts of the piedmont plain (Fig. 1). In this area the deep aquifer exhibits a semi-unconfined condition and is recharged by downward leakage from the alluvial fans of the major rivers. The turnover time of groundwater in the shallow aquifer is believed to vary in the range 200–1,000 years or more (Zhang and Payne 1997), but the proportion penetrating deeper is estimated to be much older, with isotopic signatures corresponding

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to recharge in a colder and wetter period around 10,000–20,000 years B.P., and down-dip at depth even older still (Zhou et al. 2003).

In the rural areas an average value for deep aquifer groundwater-level decline of more than 3 m/year during the period 1970–1980 has now reduced to 2 m/year. Given the confined nature of the aquifer system, such drawdown can be caused by relatively modest abstraction rates of essentially fossil groundwater. But in the case of a layered alluvial aquifer, such as this, they generate a disproportionate risk of environmental damage (land subsidence and groundwater salinisation).

Mechanisms of Aquifer Salinisation

It is essential to consider in some detail the issue of aquifer salinisation. The term refers to a variety of mechanisms whereby the salinity of groundwater gradually increases over a number of years or even decades. The principal mechanisms of aquifer salinisation on the North China Plain (Evans and Han 1999) are:

- vertical up-coning of adjacent, poor-quality groundwater into the shallow fresh-water aquifer under heavy abstraction,
- recycling of salts from irrigation water into the shallow fresh-water aquifer, aggravated by pumping of brackish groundwater for irrigation, and
- induced downward leakage of saline groundwater potentially associated with heavy abstraction and draw-down in the deep confined fresh-water aquifer.

The way in which these processes lead to progressive salinisation of the thin phreatic fresh-water aquifer on the Heilongang and to the downward migration of the saline water/fresh water interface at depth is illustrated in Fig. 4. There is field evidence from some parts of the Heilongang (notably Fucheng County) that the latter process has been occurring at rates of 0.5–2.0 m/year over the past 20 years.

Obviously, the higher the salinity of the source water, the more rapidly the process occurs. All of the processes described are distinct from the better-known seawater intrusion, in which falling groundwater levels in a coastal aquifer induce landward subsurface migration of seawater. The latter also occurs along some sections of the Bohai Sea coast (Xue et al. 2000), but is less significant than the salinisation processes described above.

One possibility for irrigation is the pumping of brackish water during parts of the irrigation cycle, thus enabling farmers to reduce pumping from the deep confined fresh-water aquifer, Although the hazard of secondary aquifer salinisation can be reduced with careful irrigation water management, the use of brackish groundwater for agricultural irrigation poses an especially complex, long-term management issue. Detailed technical assessments of soil characteristics, irrigation application rates and vadose zone hydraulic properties are required to assess and manage the salinity hazard. Moreover, educational campaigns at the level of WUAs are required in relation to the aquifer salinisation hazard and the potential consequences of continuing with some current practices.

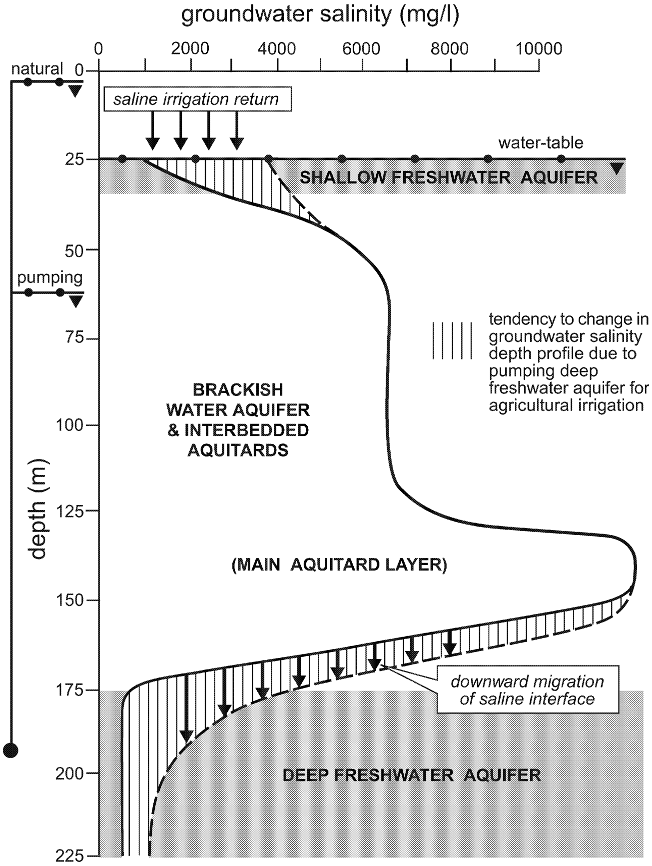

Fig. 4 Processes of salinisation of shallow and deep groundwater on the Heilongang

Options for Mitigating Aquifer Depletion

A range of water resource management strategies, which could contribute to reducing (and eventually eliminating) aquifer depletion, are discussed below. Those on the 'demand-side' are likely to make a larger and more critical contribution than those on the 'supply-side'. All of these options can be applied at local (county or district) level, but require varying degrees of facilitation and/or support at provincial, basin or national level, and are being implemented in the major World Bank-financed China Water Conservation Project under MWR coordination. This involves a series of county/district level groundwater management pilot projects, with special focus on the Guantao County and Fangshan District WRBs in Hebei Province and Beijing Municipality respectively.

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Table 7 Water-use characteristics of the most common crops and current cultivation regimes on the North China Plain

Crop type	Growth period	Typical yield (kg/ha)	Water use (kg/m^3)	Evapotranspiration	
				Total[a] (mm/year)	NBET[b] (%)
Winter wheat	Oct–May	4,000–6,000	0.8–1.2[c]	300–380	15–25
Summer maize	Jun–Sep	4,500–7,000	1.8–2.1[d]	420–500	20–30
Spring wheat	Apr–Aug	3,500–4,000	0.8–1.2[c]	350–500	25–30
Soya beans	Apr–Sep	2,100–2,700	n.a.	360–410	30–40
Vegetables	May–Aug	Variable	Variable[d]	900–1,200	Variable

[a] Both beneficial (in terms of crop production) plus non-beneficial losses under present cultivation system, the higher values corresponding to the hotter, and somewhat drier, southern counties
[b] Typical non-beneficial evapotranspiration losses as percentage of total
[c] Receives regular irrigation throughout dry spring period to achieve yields indicated
[d] Much less irrigation generally needed, since cultivated during wet summer months

Reducing Groundwater Abstraction for Irrigation

Agricultural water-saving measures

There is considerable evidence that agricultural water-saving measures can substantially reduce non-beneficial evapotranspiration (NBET) (Shen and Wang 1999)—that is, are capable of effecting ‘real water savings’. The potential order of NBET for the most important crops (as presently cultivated) is indicated in Table 7, although only a proportion of this can normally be eliminated (probably no more than 50 and 80 mm/year per crop for areas under groundwater and surface-water irrigation respectively). The value for groundwater is normally less because groundwater irrigation is intrinsically more efficient than surface water, as a result of more continuous temporal availability, smaller irrigation command area, and higher energy cost.

Additionally, in the highly permeable soils of the upper part of the piedmont plain, traditional methods of surface-water irrigation lead to high rates of infiltration, and reduction of these soil-water losses would represent more ‘energy saving’ than ‘real water saving’, because the water returns to the fresh-water aquifer and can be recovered. Care is obviously needed to distinguish this condition clearly, since failure to so do can lead to ‘double water resource accounting’ (Foster et al. 2000).

Nevertheless, it is considered that there is everywhere considerable scope for agricultural water savings (Shen and Wang 1999) through:

– *engineering measures*, such as irrigation water distribution through low-pressure pipes (instead of open earth canals) and irrigation application through drip and micro-sprinkler technology,
– *management measures*, to improve irrigation forecasting, water scheduling and soil moisture management, and
– *agronomic measures*, such as deep ploughing, straw and plastic mulching, and the use of improved strains/seeds and drought-resistant agents.

Such measures are considered capable of reducing the rate of decline in the deep confined aquifer and of making a contribution to the stabilisation of the water-table of the shallow aquifer. However, since they are heavily dependent upon water-user participation, and require metering of groundwater abstraction to confirm their effectiveness, they are likely to take numerous years to implement fully.

Changes in land use and crop regimes

If larger water savings and more rapid reductions in groundwater abstraction are needed, then consideration should also be given to changes in crop type and land use. There is significant potential to introduce higher-value, lower-water demand crops through greenhouse cultivation, but there may be significant market, transport and storage limitations on this option, and it is only likely to be feasible at present in the vicinity of major urban centres.

An even more radical option would be to place a ban on the cultivation of irrigated cereal crops in the most critical groundwater areas, and thus reduce the overall proportion of the land area used for the cultivation of irrigated winter wheat, and hold a larger part of the land area fallow until the planting of the largely rain-fed summer maize crop.

Institutional needs for implementation

The success of any of these agricultural water-saving measures in reducing the decline in aquifer water levels depends directly on the efficacy with which the reductions in irrigation lamina can be translated into corresponding permanent reductions in water-well abstractions. It is essential that agricultural water savings in some fields are not simply transferred to expand the overall area under irrigation, or to increased water use in other sectors (Foster et al. 2000).

For this purpose there are various institutional (socio-political and organisational) issues which must be addressed:

– farmers need to be well informed on the benefits of adopting more-efficient irrigation methods and need to grasp fully the ‘real water saving’ concept,
– local groundwater resource managers need to appreciate the need to set targets for WUAs on reducing abstraction,
– closer linkages must be established between the agricultural extension service promoting water-saving measures and the process of issuing groundwater abstraction permits,

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- groundwater abstraction needs to be put on a sound legal footing, by comprehensive implementation of the existing law on water-well abstraction permits,
- implementation of local water-well abstraction measurement and groundwater-level monitoring, and the dissemination of the information generated to water users,
- provision of economic incentives (such as part financing and/or easy-access low-cost loan capital) for the installation of more-efficient irrigation technology,
- a realistic 'groundwater resource fee' needs to be imposed, generating finance for aquifer management monitoring needs and serving as an incentive for reducing groundwater abstraction,
- more emphasis on the 'new roles' required of the WRBs, in terms of support to WUAs for managing and monitoring the status and use of groundwater resources, and in public and political education and awareness.

The level of groundwater depletion on the North China Plain is such that the action of an individual WRB alone will not be sufficient to stabilise the local groundwater table. For effective resource administration, Groundwater Resources Management Areas (GWRMAs) need to be defined and established (Evans and Han 1999), taking into account hydrogeologically based boundaries and 'upstream–downstream' considerations, since these provide a more rational basis for integrated water resource management (Fig. 5). A GWRMA will, of course, often contain more than one groundwater body, and will require an aquifer management organisation involving representatives of a broad range of stakeholders. For the most part it appears that reasonable GWRMAs could be defined respecting county boundaries and (for administrative convenience) could largely remain within a single province. But the same cannot be said of municipalities.

At the urban–rural interface there is need to promote groundwater resource reallocation to the more productive commercial and industrial users, through schemes in which the corresponding municipality finances improvements in agricultural irrigation (generating real water savings) in return for abstraction and use rights of a proportion of the groundwater saved. Similarly, in areas with adequate knowledge of groundwater resource availability and behaviour, the introduction of tradable water rights could be considered, provided a sound water-use rights system had been consolidated.

Where groundwater resource management is concerned, it will be important to reconcile the 'bottom-up' and 'top-down' approaches, and a possible scheme for this is illustrated in Fig. 6. Some key considerations in this respect are:

- the identification and prioritisation of GWRMAs should be conducted by the MWR with close interaction with the corresponding RBC and the PWRBs (Provincial Water Resources Bureaux),
- target yields should be defined for each GWRMA (and component aquifer unit), through dialogue between the RBCs and the PWRBs, and then related to water-well abstraction permits and implemented by the WRBs, raising any special concerns as necessary,
- in order to improve central policy (through sharing of success and difficulty), feedback from the county/district level via the PWRBs and the RBCs will be necessary,

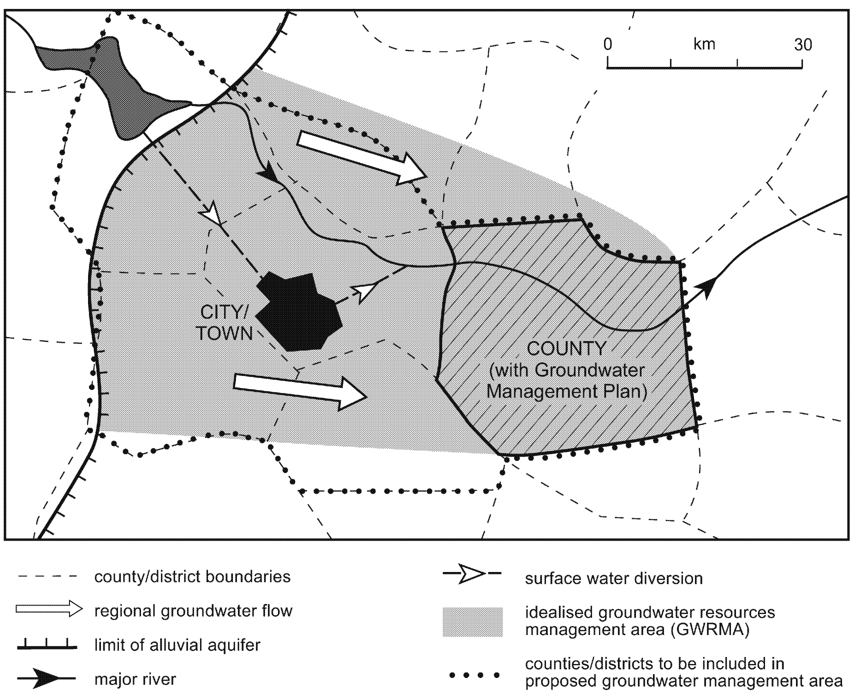

Fig. 5 Theoretical example of consolidation of neighbouring WRB (county/district) areas into a GWRMA

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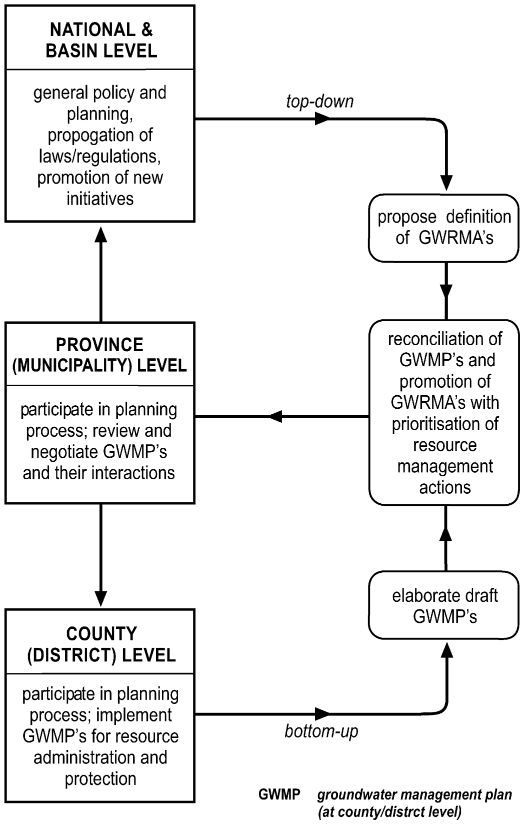

Fig. 6 Preferred hierarchy of communication and action for the establishment of GWRMAs

– the long-term MWR role with respect to groundwater management should be facilitating and monitoring actions of the PWRBs, as well as promoting interchange at all levels,
– the MWR could establish more harmonised criteria for the administration of groundwater abstraction permits, especially as regards their period of guarantee, taking into account the minimum duration necessary to give financial institutions confidence to invest in the related development (including appropriate water-savings measures) and the need to reserve groundwater for human consumption,
– it must be recognised that stabilising the Quaternary Aquifer of the North China Plain is a long-term process, and that the advocated demand management approach will require appropriately trained staff in the CWRBs and public awareness raising programmes for water users, political decision makers and the general public.

Aquifer Recharge Enhancement with Excess Surface Runoff

While agricultural water savings are capable of making a major contribution towards reducing the decline in groundwater levels, they may not everywhere be sufficient to close the imbalance of groundwater resources. Thus, complementary actions, such as artificial aquifer recharge of excess surface runoff in the summer months of the wetter years (deploying relatively low-technology methods) (Table 8), are also required. Moreover, there is need for aquifer recharge enhancement on the piedmont plain in particular because of:

– the existence of much larger groundwater storage deficits in most of the many urban centres of the area, and
– the fact that the deficit of natural recharge against actual abstraction is much more marked in dry years.

China already has considerable experience of artificial aquifer recharge from the 1970s (Tian et al. 1990; Liu et al. 1994; Institute of Hydrogeology & Engineering Geology 1995; Evans and Han 1999). The main techniques used vary considerably with general hydrogeological setting and specific subsoil profile but include:

– small gully dams on fast-flowing rivers in the upper piedmont plains within the alluvial fan environment,
– rubber dams, flow-deflecting channel baffles and other riverbed dam structures to increase time and head available for riverbed recharge in the braided river systems of the piedmont plain,
– intermittent flooding of maize fields following wet season storms, and occasional excess surface-water irrigation at other times on other selected crops,
– diversion of river flows to large flood-retention reserve land (up to 100 km^2 in area along the major rivers) for both flood relief and aquifer recharge,
– diversion canals fitted with large-diameter recharge well sumps, generally on the alluvial flood plain,
– use of village pits and ponds (usually of 3,000–5,000 m^3 capacity), whose beds are cleaned prior to the wet season, by collecting local surface runoff and excess irrigation canal flow during heavy rains.

Table 8 Aquifer recharge enhancement techniques potentially suitable for the North China Plain (+++ highly applicable, ++ moderately applicable, + somewhat applicable, *o* not applicable)

Recharge technique	Source of water for recharge		
	River flow	Flood runoff	Urban wastewater
In-channel flow retention	++	+	o
Land spreading	++	++	+++
Ponds/pits and canals/trenches	+++[a]	++	++
Injection boreholes	+	o	o

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All of the above measures should continue to be encouraged, especially in the piedmont plain environment where the conditions are very suitable. The issue generally is not so much the feasibility of artificial aquifer recharge but more the regular availability of water to recharge. Moreover, some flood-water flow to the sea is needed to flush sediments and pollutants from riverbeds, and this is a further competing consideration.

There are a number of potential institutional impediments which will need to be overcome, especially the financial, administrative and legal basis for using surface runoff in upstream counties principally for the benefit of groundwater users in downstream counties. And it will probably be necessary for PWRMBs and/or the provincial governor to oversee the establishment of the required water reallocation system and the negotiations to reach agreements on implementation.

Aquifer Recharge with Urban Wastewater

The current rate of generation of urban and industrial wastewater in the Hai River basin alone is very large indeed (in the order of 10,000 Mm^3/year). In most cases wastewater is generated from combined residential and industrial sewers which, in many instances, will also carry surface drainage waters following heavy rains. Wastewater quality varies widely with the level and type of industrialisation in the cities and towns involved, and with other factors such as the natural soil salinity in the urban area concerned. In recent years the construction of wastewater treatment plants to secondary or higher level has suddenly become vogue, regardless of their high capital cost and onerous operational cost implications.

Most urban wastewater should be regarded as a valuable water resource which, after primary (or perhaps secondary) treatment, can be reused directly for the irrigation of certain agricultural crops. Such irrigation, which (of necessity) is of relatively low efficiency, normally results in high rates of infiltration and recharge to aquifers when practised on permeable soils (Foster et al. 1997), like those of the piedmont plain.

Moreover, the wastewater can, under suitable hydrogeological conditions, be used for some techniques of aquifer recharge (Table 8; Foster et al. 1994). This can also overcome the problem of wastewater storage or discharge during winter and in the wettest summer months when there is no crop water demand for irrigation. The natural process of infiltration through the vadose zone will normally affect secondary and tertiary treatment for most wastewaters.

At the same time, uncontrolled wastewater discharge and/or reuse often presents a serious groundwater pollution threat. The problem of potential pollution of groundwater can be overcome (Foster et al. 1997) by:

- careful site selection to avoid hydrogeological unsuitable locations,
- detailed study of wastewater chemistry and avoiding the generation of unacceptable wastewaters (normally by imposing more stringent site sewer discharge controls and/or modification to the sewerage system),
- separation in space and/or in depth of the part of the aquifer used for wastewater recharge and irrigation recovery from parts used for drinking-water capture.

Significant institutional as well as technical challenges will have to be overcome for the successful implementation of wastewater reuse schemes. It will be necessary for the relevant EPBs to guarantee acceptable wastewater quality and treatment standards in the interest of the WRB(s) authorizing the reuse, and appropriate financial, administrative and legal arrangement will need to be in place for this to be possible, together with considerable training of the staff of these bureaus on the operation and control of such schemes.

There is an urgent need to form working groups of groundwater specialists and wastewater managers to undertake detailed assessments of the possibilities of using urban wastewater for reuse in the above way. Such working groups would probably benefit from the inputs of an international adviser in the first instance. Following on from this, there will be need for the promotion of some relatively large-scale pilot demonstration projects at sites believed to be representative of wastewater types and hydrogeological settings for the North China Plain.

Concluding Remarks

The sustainability of intensive groundwater development for irrigated agriculture on the North China Plain constitutes one of the world's major water resources management issues, whose implications are potentially very serious. The approaches to groundwater resources management discussed constitute an attempt to buffer the serious socio-economic impacts which are likely to be experienced from continuing with essentially uncontrolled abstraction. Critical to the success of the options presented is that the 'agricultural water savings' achieved result in reduced groundwater abstraction, and not an expansion in irrigated area or industrial production. Significant strengthening of political resolve and institutional capacity will be required to ensure that this occurs.

It is recommended that groundwater in the down-dip deep fresh-water aquifer be treated as a strategic water-supply reserve, which in the long-term should only be tapped for:

- high-value, small-demand uses, where no other ready alternative resource exists, and
- to alleviate water-supply shortages in extreme drought conditions.

While adoption of this policy is pressing, its implementation is not straightforward and will require a change in the balance of economic activity on the Heilongang and the widespread introduction of major incentives for real water-saving measures.

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References

China Institute of Geosciences (2000) Assessment of present groundwater resources in the Hai River Basin and analysis of environmental and geological effects in a typical area. Hai River Basin Resources Commission Report

Crook FW (1999) China's quest for food-grain security. Washington J Mod China 5(2):13–14

Evans R, Han Z (1999) Groundwater: Hai, Huai and Huang River basins. World Bank China Water Sector Action Plan Program Study

Foster SSD, Lawrence AR (1995) Groundwater quality in Asia: an overview of trends and concerns. UN-ESCAP Water Resources J Series C 184:97–110

Foster SSD, Gale IN, Hespanhol I (1994) Impacts of wastewater use and disposal on groundwater. BGS Tech Rep WD/94/55 (in association with WHO)

Foster SSD, Lawrence AR, Morris BL (1997) Groundwater in urban development: assessing management needs and formulating policy strategies. Washington, DC, World Bank Tech Paper 390

Foster SSD, Chilton PJ, Moench M, Cardy WF, Schiffler M (2000) Groundwater in rural development: facing the challenges of supply and resource sustainability. Washington, DC, World Bank Tech Paper 463

Garduno H (2001) Water rights administration: experience, issues and guidelines. UN-FAO Legislative Study 70

Hai River Basin Resources Commission (1997) Water supply and demand planning for the middle and long term in the Hai River basin—2000 and 2010. Hai River Basin Resources Commission Report

Han Z (1997) Groundwater for urban water supply in northern China. In: Proc IAH 37th Congr Groundwater in the Urban Environment, September 1997, Nottingham, vol 1, pp 331–334

Institute of Hydrogeology & Engineering Geology (1979) The hydrogeological atlas of the People's Republic of China. Atlas Publishing House, Beijing, China

Institute of Hydrogeology & Engineering Geology (1995) The study of rational utilisation of groundwater resources and techniques for interception of floodwater for artificial recharge of groundwater in the Yellow River basin. Ministry of Geology and Minerals Report

Lin X, Shu L (1992) Aquifer overexploitation and environmental effects. In: Proc Int Conf Groundwater and Environment, August 1992, Beijing. Seismological Press, Beijing, pp 6–9

Liu P, Liu Z, Duan Z (1994) A case study on artificial recharge of groundwater in the coastal aquifer of Longkou, China. In: Proc ASCE 2nd Int Symp Artificial Recharge of Groundwater, pp 464–470

MWR (1992) Water resources assessment for China. Ministry of Water Resources, Water & Power Press, Beijing, China

Shen Z, Wang L (1999) Study of real agricultural water saving. Beijing, World Bank/China Institute of Water Resources & Hydropower Res Report

Tian Y, Zhang Y, Sun X (1990) Artificial recharge of groundwater in the Huang-Huai-Hai Plain. Water Resources & Power Press, Beijing, China

Xue Y, Wu J, Ye S, Zhang Y (2000) Hydrogeological and hydrogeochemical studies of salt-water intrusion on the south coast of Laizhou Bay, China. Ground Water 38:38–45

Yellow River Water Resources Commission (1997) Water supply and demand planning for the middle and long term in the Yellow River basin—2000 and 2010. Yellow River Water Resources Commission Report

Zhang Z, Payne BR (1997) Environmental isotope study related to groundwater age, flow system and saline water origin in Quaternary aquifers of the North China Plain. In: Proc IAEA Conf Isotope Hydrology for Asia and the Pacific, Beijing, June 1997, Vienna

Zhou L, Lui C, Jiang S, Gao S (2003) A study of ^{36}Cl age of Quaternary groundwater of the Hebei Plain, China. Sci China (in press)

 DOI 10.1007/s10040-003-0300-6