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Can urbanization solve inter-sector water conflicts? Insight from a case study in Hebei Province, North China Plain

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Abstract

China, like many countries, is experiencing an unprecedented rate of urbanization. Urbanization is usually thought to intensify inter-sectoral water conflicts. In contrast, this paper considers urbanization as part of a viable solution to the problem. By evaluating water *consumption*, or depletion, in terms of actual evaporation and transpiration, as opposed to the amount *withdrawn* from water sources, this paper argues that urbanization has a positive role to play in lessening inter-sectoral water competition and in reversing groundwater declines. At the regional scale, urbanization can help achieve these goals by replacing some agricultural land use, particularly under two conditions: (1) both the industrial and agricultural sectors adopt water-saving technologies, and (2) urban wastewater and runoff are treated and reused directly in agriculture or indirectly through artificial recharge. Combined, the two conditions must result in a net decrease in water consumption at the regional scale. These points are illustrated with a case study of rural Luancheng County and adjacent industrialized Shijiazhuang City in Hebei Province. A water-balance approach provides a simple, quantitative framework for evaluating the potential for various land-use mosaics to stabilize groundwater levels.

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1. Introduction

Propelled by the economic reforms of the late 1970s, the Chinese economy has experienced remarkable and sustained growth. Over the past two decades, the gross domestic product (GDP) has maintained an average annual growth rate of about 10% (NSBC, 2004). From 1978 to 2004, when China's population reached 1.3 billion (more than 20% of the world's population), the real GDP increased more than 10-fold.

With economic growth, China's rate of urbanization has also increased. From 1980 to 1997, China's urban population grew at an average annual rate of 0.62% (Liu & Chen, 2001). By 2004, the urban population accounted for 40% of the total population, compared to 19.4% in 1980 (NSBC, 2004). As China continues its dramatic economic transformation, urbanization is fully expected to accelerate, fulfilling a strategic priority for China's socio-economy to approach the level of moderate developed countries by the middle of this century. In its most recent assessment, the UN Population Division predicted that, by 2050, the urban population will reach 1 billion, comprising two-thirds of China's total population.

This shift from rural to urban land use and from agriculture to industrial production profoundly impacts the use of water resources and has provoked competition between different sectors. During 1949–2004, total water use in China increased more than five-fold, from 103 billion cubic meters (bcm) to 555 bcm (MWR, 2004). To promote industrialization, the Ministry of Water Resources and its sub-provincial agencies prioritize water allocation to urban and industrial uses over irrigation (Lohmar *et al.*, 2003), exacerbating already severe agricultural water shortages, particularly in northern China. During 1949–2004, the share of water allocated to the agricultural sector declined from 97% to 65%, while the share of water allocated to the industrial sector increased from 2% to 22%. The share of domestic water use also has increased (MWR, 2004). Inefficient water allocation between sectors deepens the competition for water between agriculture and industry, and many analysts (e.g. Lohmar *et al.*, 2003) predict that, as urbanization continues, inter-sectoral competition for water is likely to intensify.

Urbanization and industrialization not only have increased water competition between sectors, but also have caused serious water pollution problems. Water use per unit of industrial output is exceptionally high in China, and about 50% of industrial wastewater is discharged without treatment to standards (World Bank, 2006). In 1993, China discharged an estimated 35.6 billion cubic meters of untreated wastewater (United Nations ESCAP, 1997), including more than 5.3 million kilograms of organic water pollutants per day – about equal to the *combined* emissions of the United States, Japan, and India (Heilig, 1999). Wastewater generation in China is expected to reach 59–78 billion m^3/yr by 2030 (Liu *et al.*, 2001). Severe pollution from untreated urban wastewater discharge contaminates stream channels and shallow aquifers, further depleting the quantity of usable fresh water. Conversely, water shortages exacerbate contamination because streams that lack natural flow cannot dilute the untreated wastewater that enters them (Zhou, 1995; Ma & Ortolano, 2000).

To date, it appears that urbanization has only served to worsen the competition for water between sectors. In this paper, we ask a seemingly counterintuitive question of what role, if any, urbanization may have in *reducing* inter-sector water competition. We note that, although *withdrawals* for urban water use may be large, urban water *consumption* generally is much less than agricultural water consumption, on a per area basis. Thus, a key to relieving inter-sector water conflicts in the face of rural-to-urban land-use change is to capitalize on this paradox by maximizing the reuse and minimizing the consumption of water withdrawn for urban supplies. This strategy relies on improving industrial water-use efficiency and treating urban wastewater. We focus particularly on the potential for urbanization to alleviate severe groundwater shortages in the North China Plain, where aquifers supply water for both urban and agricultural uses.

While the social and economic benefits and costs of urbanization have been analyzed extensively (Fu, 2001; Gao, 2001; Liu *et al.*, 2003; World Bank, 2001), the hydrologic impacts have not. Taking a water-balance perspective, this paper explores the hydrological linkages between urbanization and the availability of groundwater for agriculture, with the aim of providing policy insights on, and options for, managing inter-sectoral competition for water resources in the particular context of the North China Plain. The specific objectives are to:

(a) Assess the water balance in groundwater irrigated agricultural areas of the North China Plain. Using the case of Luancheng County, Hebei Province, we show that the existing water supply is over-allocated, and stabilizing groundwater declines requires reducing current rates of water consumption, or depletion.
(b) Examine various alternative options for resolving water problems, by focusing on water consumption.
(c) Consider the hydrologic impacts of urbanization, referring to Luancheng County's neighbor, Shijiazhuang City.
(d) Offer a simple, quantitative approach for planning a mosaic of future landscapes which together consume no more water than is naturally replenished to the North China Plain, and therefore can effectively arrest groundwater declines. Though urbanization alone cannot stabilize declining water supplies, we show how it can be part of an integrated solution.

Although industrial pollution affects groundwater resources as seriously as overdrafts, this paper primarily addresses the depletion of groundwater due to alterations of the natural water balance. Likewise, although social, political, and economic considerations are crucial determinants of water management, this paper focuses primarily on the hydrologic aspect. We hope to contribute a sound scientific basis to the overall, interdisciplinary quest for sustainable water management policy in a changing economic setting.

2. North China Plain case study

The 320,000 km^2 North China Plain (Figure 1) is China's most important center of agricultural production and also home to more than 200 million people. It produces more than 50% of the nation's wheat and 33% of its maize (State Statistics Bureau, 1999).

The North China Plain is urbanizing at an even faster pace than the nation as a whole. For example, in the Shijiazhuang area (see Figure 1), the population increased by 3.1% in 2005 alone and urban areas now account for about 43% of the total population (Sjzchina, 2006). Liu *et al.* (2003) predict that, by 2030, urban populations in provinces of the North China Plain will range from 58–90% of their total populations.

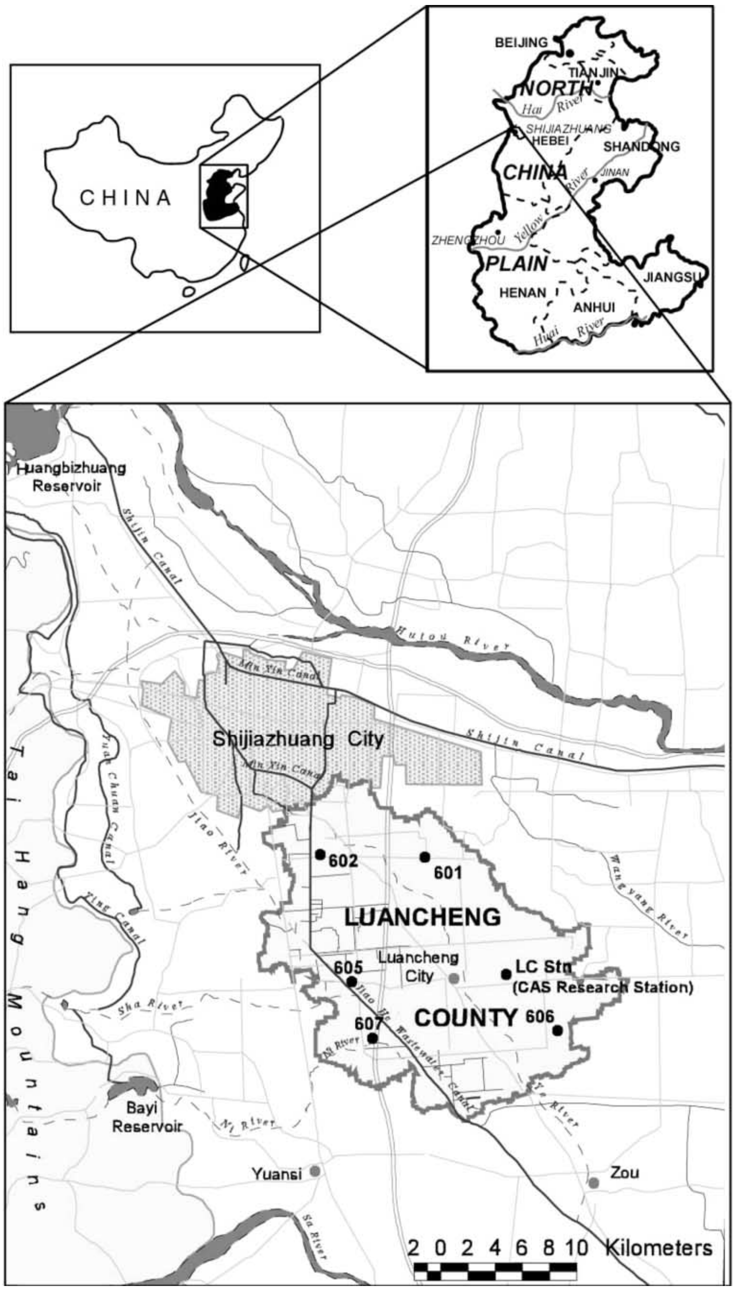

Fig. 1. Luancheng County and Shijiazhuang City: locations and features. Black dots indicate monitoring wells. The upper right inset depicts the North China Plain.

In the North China Plain, water is the most vital and limiting natural resource (Brown & Halweil, 1998; World Bank, 2001). Virtually all clean surface water is diverted into cities for municipal use, leaving rural industries and agriculture to compete over a diminishing groundwater resource, even as production continues to increase. Consequently, natural streamflow has almost completely ceased, groundwater levels are declining steadily (Figure 2), salt water is intruding into previously fresh-water aquifers, and in many places the land surface is subsiding. Even the largest cities, which receive highest priority for water distribution, undergo repeated "crises" set off by water shortages.

For hundreds of years, farmers accommodated the weather patterns by producing at most two to three crops every 2 years (Dong, 1991). Only since the 1960s has groundwater irrigation provided the deficit water supplement that allowed farmers to produce two crops reliably every year. Quaternary alluvial deposits extend to a depth of more than 500 m beneath the land surface in the center of the plain (Hebei Province Department of Geology & Mineralogy, 1992). These deposits comprise the aquifers that supply groundwater to the North China Plain.

Rapid groundwater depletion beneath the North China Plain has been a serious concern at least since the mid-1970s, when it was first documented (Zhu & Zheng (1983). The average rate of groundwater decline in the shallow Quaternary aquifer is about 0.5 m/yr (Foster *et al.*, 2004). Despite more than 20 years spent addressing the problem, groundwater reserves continue to deplete steadily throughout the North China Plain (Ministry of Water Resources, issued annually).

Efforts to reverse water-table declines have focused on improving irrigation efficiency, or the ratio of water consumed to water supplied to crops. The first substantial improvements corresponded with a shift from high-capacity, collectively managed irrigation wells to small-capacity, privately managed wells, beginning in the late 1970s (Wang *et al.*, 2005). The reduction in conveyance and field losses associated with private well management significantly reduced the need for groundwater pumping to supply irrigation water. More recently, canal lining and precision irrigation techniques have further improved irrigation efficiency. As a result, total groundwater pumping for irrigation has decreased by more than half. For example, pumping in Luancheng County, Hebei Province (Figure 1) was about 39 cm/yr in 1996, compared to about 102 cm/yr in 1976, with no losses in crop yield (Hu, 1996).

Yet, despite significant achievements in irrigation efficiency, groundwater declines have persisted, unabated. Figure 3 explains this paradox in terms of the example of Luancheng County (Kendy *et al.*, 2003a, b; 2004). Before irrigation development and during the early years of small-scale irrigation, precipitation exceeded evapotranspiration[1]. Excess water recharged the underlying aquifer and at times even filled the aquifer to capacity, generating runoff. Later, as the irrigated area grew and double cropping became widespread, crop evapotranspiration increased until it surpassed precipitation. In order to maintain the continuous cropping pattern, another water source was needed to satisfy the deficit between 46 cm/yr of precipitation and 66 cm/yr of evapotranspiration. That additional water comes from groundwater mining. Assuming a specific yield[2] of 0.2, the quantity mined (20 cm/yr) corresponds to a 1 m/yr groundwater decline, fully in line with observations.

Thus, despite a significant decrease in pumping, the water table continues to decline at a nearly constant rate of about 1 m/yr. All crops require a certain quantity of water – in this case 66 cm/yr (Kendy *et al.*, 2004) – regardless of the amount applied. If they receive 100 or 1,000 cm/yr, they will still consume 66 cm/yr, and the rest will drain through the soil profile. So long as all crop-water requirements are met, any reduction in pumping for irrigation triggers a corresponding reduction in groundwater

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[1] The groundwater budget for Luancheng County indicates that lateral inflows balance lateral outflows (Kendy, 2002), so only precipitation and evapotranspiration are shown in the figure.

[2] Specific yield, or drainable porosity, of 0.2 means water occupies 20% of the aquifer volume; geologic material (primarily sand and silt) occupies the other 80%. Therefore, removing 20 cm of water causes the water table to drop 1 m.

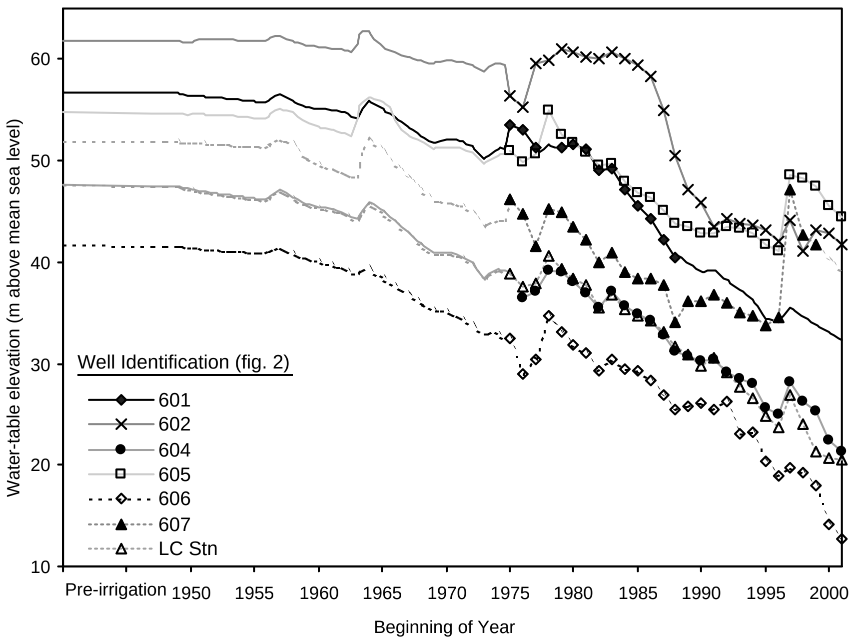

Fig. 2. Annual water-table elevations in observation wells in Luancheng County, pre-irrigation through 2000. Well locations are shown in Figure 1. Symbols indicate monthly average December measurements (Hebei Water Resources Bureau, unpublished data). For years without data, lines show water levels calculated by groundwater flow model (Kendy, 2002).

recharge (infiltrated precipitation and excess irrigation water, which percolates through the soil profile, down to the water table) from irrigated cropland.

Figure 4 illustrates how this happened in Luancheng County. The decrease in pumping that began in the late 1970s corresponds with the transition from large-capacity, communal wells to small-capacity, private wells. Not only were the private operators less apt to over-irrigate, but transmission losses also decreased because conveyance distances were shortened. But the rate of areal recharge decreased in sync with the pumping (Peaks in areal recharge occurred during years with above-normal precipitation).

The net impact on water-table declines is nil. This also explains why lining canals and ditches to reduce seepage has no effect on water-level declines, and in fact saves no water in the North China Plain. Evapotranspiration is the only water actually consumed, or depleted, from the hydrologic system.

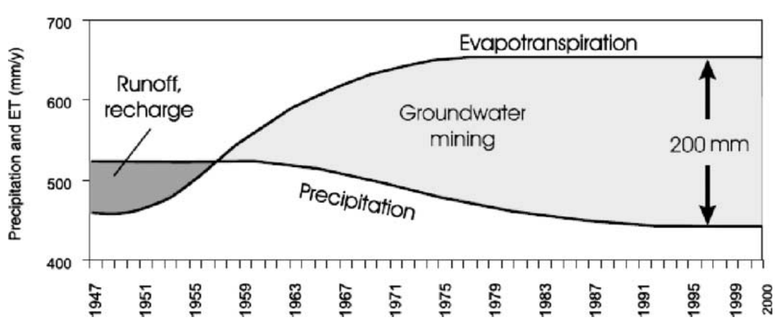

Fig. 3. Precipitation and evapotranspiration for cropland in Luancheng County, 1947–2000.

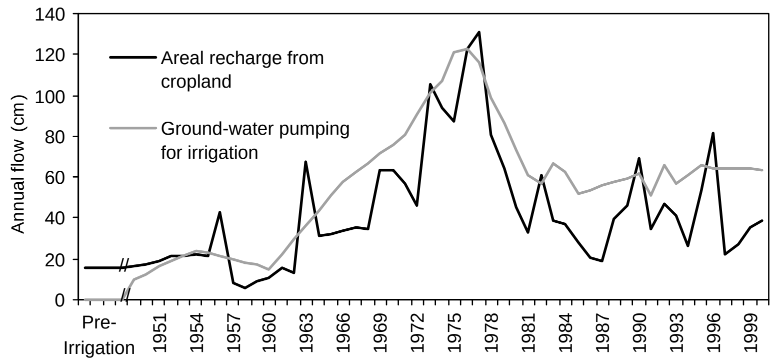

Fig. 4. Relationship between groundwater pumping for irrigation and areal recharge from cropland to the underlying aquifer, Luancheng County, pre-irrigation period to 2000. Sources: Hu (1996), Shijiazhuang Water Conservation Bureau (issued annually) and Kendy *et al.* (2004).

3. Balancing the water budget: options for a sustainable future

Although conceptually the water-balance analysis summarized in Figure 3 is both straightforward and intuitive, it is commonly neglected in water-policy analysis. For example, by ignoring depletion due to crop evapotranspiration, Nickum (1998), optimistically concluded that: "Groundwater overdraft does not deplete the resource, which is continuously renewed...Aquifers will replenish with reductions in withdrawals" and, furthermore, "…the 'water crisis' in China is localized, and is economic and institutional rather than one of a vanishing resource".

On the contrary, by considering the overall water balance, we can see that groundwater depletion is as regional as groundwater-irrigated cropland – the major land use on the North China Plain – and that the water resource is, indeed, "vanishing" into the air through evapotranspiration. Therefore, arresting the water-table decline will entail more than local institutional changes. Groundwater declines will slow only when water consumption decreases, and will reverse only when replenishment exceeds consumption. This goal may be achieved either by increasing inflows or by decreasing outflows.

3.1. Interbasin water transfers

Nanshui Beidiao, the engineering scheme to transfer water from the Yangze River in southern China to the North China Plain, will increase inflows. The world's largest water transfer project, *Nanshui Beidiao* is designed to divert more than 40 cubic kilometers per year from the Yangtze River basin to the North China Plain by 2050 (Liu, 2003). However, water deliveries will be targeted primarily to cities and not to irrigated cropland (Liu & You, 1994; Liu, 1998; Nyberg & Rozelle, 1999). If, as expected, the south-to-north water diversions provide adequate supplies to meet urban water needs, then some of the water currently being allocated to urban areas potentially could be re-allocated back to agriculture. In addition, rural areas potentially could reuse the increased quantity of urban wastewater after treatment and discharge and treatment. Nevertheless, the transfers will be much less than what is needed to fill the regional deficit between precipitation and evapotranspiration. Thus, *Nanshui Beidiao* will provide a critical water supplement to some local areas, but will not by itself abate regional groundwater declines.

Therefore, the remainder of this and the following section focus on demand management. Unlike supply development, which targets specific receiving areas, these demand-management options may have the potential to alleviate regional water shortages stemming from agricultural water use throughout the North China Plain.

3.2. Crop changes

Because the predominant winter-wheat/summer-maize rotation is water-intensive, many people have called for crop changes to balance the water budget. Recommendations include introducing more drought-resistant crops (Nyberg & Rozelle, 1999), encouraging greenhouse cultivation, banning cultivation of irrigated cereal crops in key locations (Foster *et al.*, 2004), replacing summer maize with spring maize every other year (Yu, 1995), increasing maize production while decreasing wheat production, and stopping wheat production altogether (Yang & Zehnder, 2001). Others focus on increasing the economic productivity of irrigation water by replacing grain crops with relatively high-value crops such as vegetables and turf, a trend that is already evident in Luancheng County.

Kendy *et al.* (2004) assessed hydrologic impacts of various cropping changes by simulating annual evapotranspiration and groundwater recharge in Luancheng County under five different winter/summer crop combinations, taking into consideration the actual climate conditions and irrigation practices from 1962 to 2000. Typical planting and harvest dates were assumed. The resulting cumulative water-table changes were then calculated by subtracting inflow (model-calculated recharge) from outflow (pumping for irrigation) for each crop combination and assuming a specific yield of 0.2.

Results (Figure 5) indicate that, regardless of which summer crop is grown, irrigated agriculture is not sustainable if winter wheat is also grown. The impact of substituting maize with sweet potato is minimal, since both crops consume about the same amount of water. In contrast, by forgoing a winter wheat crop, various degrees of significant water savings can be achieved. The amount saved depends primarily on the length of the growing season, and secondly on the root depth and leaf area (Kendy *et al.*, 2003a, 2004). Figure 5 indicates that, if Luancheng County had produced only cotton and millet since 1962, the water table would have remained stable. Vegetables, which comprise early- and late-season crops grown consecutively on the same land, deplete more water due to their longer combined growing season. Because excess irrigation water replenishes the underlying aquifer, the quantity of irrigation water applied would not alter these results, so long as all crop-water requirements are met.

Thus, of the proposed crop changes, those that involve the reintroduction of annual winter fallowing offer the only means of alleviating groundwater declines, independent of other land-use changes. For social and economic reasons, land fallowing is not likely to be accepted except, perhaps, in alternate years, allowing for three crops (instead of the current four crops) per two years. However, simply substituting vegetable crops for wheat/maize is unlikely to generate sufficient water savings, due to the extended growing season of vegetables compared to maize[3].

[3] Although individual vegetable crops may require shorter growth periods than maize, farmers can grow multiple vegetable crops in a single season, resulting in a longer growing season overall than for maize.

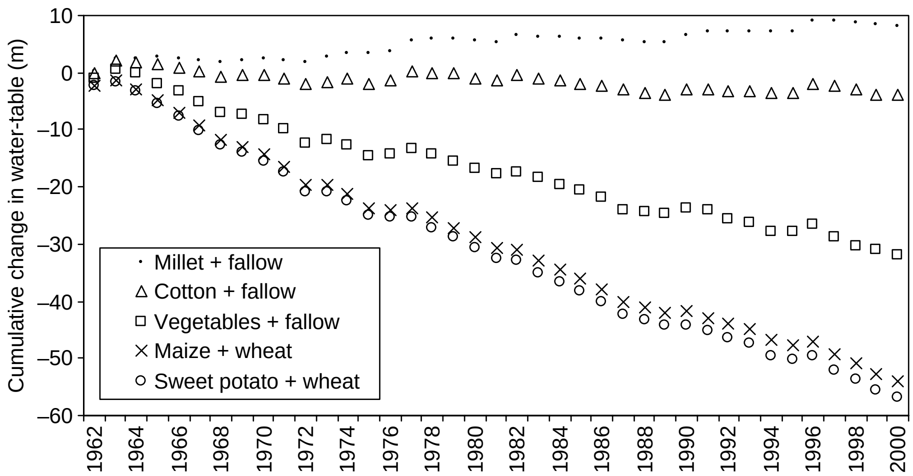

Fig. 5. Estimated groundwater declines that would have resulted from five different summer/winter crop combinations under typical irrigation practices, given historical climate conditions in Luancheng County, 1962–2000.

3.3. Agricultural water-saving technology

Improving irrigation efficiency is the most commonly advocated and politically palatable approach to reducing groundwater declines (Shin, 1999). However, most water-saving technologies for improving irrigation efficiency are inappropriate for most parts of the North China Plain. Specifically, technologies designed to reduce seepage from the soil profile cannot reduce groundwater declines beneath cropland underlain by unconfined aquifers. For example, low-pressure, underground pipeline conveyance systems are rapidly spreading across the North China Plain (Nyberg & Rozelle, 1999). These underground systems may result in more water depletion than savings, because instead of simply evaporating water from the ditch surface during conveyance periods, the additional crops that grow above the buried pipes now evapotranspire from the entire root depth throughout the growing season. Likewise, sprinkler irrigation may be wholly inappropriate for the climatic and geologic conditions of the North China Plain. First, sprinklers reduce seepage through the soil profile, which recharges underlying aquifers. Second, spraying fine droplets into the dry, windy air is likely to increase evaporation compared to traditional flood irrigation.

Thus, water levels will continue to decline, even if agricultural “water-saving” techniques are introduced, because while these techniques reduce pumping, they simultaneously decrease irrigation return flow, or groundwater recharge (Figure 4). The net effect has no impact on the water balance. As long as extensive crop cover is maintained and groundwater irrigation is used to meet crop-water requirements, the rate of water loss from the aquifer remains constant.

On the other hand, technologies that reduce the evaporation component of evapotranspiration do reduce outflow from the overall hydrologic system, and therefore can save water. However, the scope for reducing evaporation is relatively small, because the crop cover is dense and the time period between crops is typically quite short. For example, mulching winter-wheat and summer-maize with plastic membranes or straw has been shown to reduce evaporation by 10 (You & Wang, 1996) to 13.5 cm/yr (Zhang Yongqiang, 2001, Shijiazuang Institute of Agricultural Modernization, personal communication) in the North China

Plain without decreasing productivity. Greenhouses also can potentially save water, because their artificially humid, windless environment reduces evaporation.

Although the amount of irrigation water that potentially could be saved is much less than the amount consumed, if implemented over the entire cropped area, the total volume of water saved would be significant. Therefore, agricultural water-saving technologies that reduce evaporation will be critical for stabilizing declining water tables and alleviating inter-sector water conflicts.

3.4. Water pricing

Water has long been subsidized in China (Xu, 1987), and prices are far below those in most other industrialized countries. To encourage water conservation, economists have advocated raising the price of water to better reflect its actual cost (Lampton, 1983; Zhang & Zhang, 1995; Nyberg & Rozelle, 1999; Anderson & Leal, 2001). It is questionable whether raising the price, and consequently reducing incomes for relatively poor rural producers, is acceptable. For this to be politically feasible, other off-farm employment opportunities must exist.

Even if the economic challenges were met, it is not clear that such a policy change would necessarily alleviate water shortages on the North China Plain. Initial customer response to a commodity price increase is usually to reduce consumption of that commodity. In the case of irrigation water, farmers are likely to invoke practices that reduce their pumping needs. However, as we have shown, seepage reductions concomitant with pumping reductions result in no net change in groundwater depletion rates. Therefore, water price increases would only impose undue financial burdens on already cash-strapped farmers without solving the intended problem.

Higher prices can be justified only if water pricing is used to encourage land-use change. In the past, farmers had no choice but to continue farming in order to meet grain quotas. Recent abolishment of quotas might provide an opportunity for water pricing to stimulate the necessary reduction in irrigated area (Nyberg & Rozelle, 1999). According to Foster *et al.* (2004), farmers reduce irrigation applications when the water table drops deeper than 50 m below the land surface, increasing pumping costs to more than US $20 (CY 160)/ha per lamina. However, it is unclear how high prices would need to be before they cause farmers to forgo irrigation entirely, and prices may well have to be many times higher than they are now to induce such behavior. Also, logistical problems with pricing water volumetrically and monitoring deliveries make irrigation-water pricing policy difficult to implement effectively.

Industrial water users are more logical candidates for water price increases than irrigators because of the advantages of industrial water-use efficiency (discussed below). Moreover, with their much larger profit margins than farmers, industrialists have a better ability to pay, improving chances of successful implementation. Also, their use and quality of discharge water can be more easily monitored than agricultural users. Past observers noted that: "...policies designed to accelerate economic growth (by encouraging enterprise profitability) clash with the objectives and needs of a sound water price policy" (Lampton, 1983). But more recently, as water demand grows relative to supply, industrial water price increases are gaining acceptance as people realize that sustained economic growth depends upon a secure water supply. Recently imposed industrial water-resource fees encouraged a pharmaceutical manufacturer in Luancheng County to introduce technology which reduced its water use from 440 to 100 m^3/d (Kendy *et al.*, 2003b).

4. Urbanization: potential to relieve water competition

Urbanization is not normally among the options considered for balancing the water budget. However, by contemplating urbanization in the overall context of a regional water balance, we take a new look at this inevitable process not as the source of problems for which it is so often blamed, but rather as an integral part of a potential solution.

4.1. Impact of urbanization on regional water supply

Urbanization markedly influences hydrology. Urban land surfaces tend to be impermeable. In Beijing, for example, satellite images and land-use surveys indicate that the area occupied by paved roads increased by 250%, from 42 million in 2000 to 105.7 million m^2 in 2003 (Lelan M. Miller, 2006, University of Texas, written communication). Consequently, precipitation runs off, rather than recharging the aquifer beneath the city. Over-pumping groundwater from beneath a city exacerbates the problem. Together, the reduced recharge and excess discharge cause the water table to deform into a funnel shape, or “cone of depression”, beneath the city, which in the North China Plain extends laterally far beyond many city limits (Liu *et al.*, 2001). Therefore, groundwater beneath urban areas and their surroundings tends to be deeper than in other parts of the North China Plain, and may flow toward city pumping centers from all directions, regardless of the position in the regional flow path. For example, the center of the Shijiazhuang City cone of depression (Figure 6) is more than 10 m deeper than at Luancheng County’s well number 602, shown in Figure 1 (Hebei Water Resources Bureau, unpublished data). In the Cangzhou urban area, groundwater withdrawals of about 200 Mm^3/yr depress water levels by about 5 m/yr; in the Tianjin urban area, the land has subsided as much as 3 m due to reduced hydraulic pressure within the groundwater pumping-induced cone of depression (Foster *et al.*, 2004).

Unlike irrigation, most urban water use does not necessarily deplete basin resources. Most municipal water used for drinking, sanitation, bathing and cooking eventually discharges into sewage systems rather than evaporating. With the exception of water used for industrial cooling, only a small fraction of water delivered to industries actually evaporates.

However, municipal and industrial discharges can be highly polluted. Therefore, wastewater treatment is imperative for healthy water systems. By reducing polluted discharge, wastewater treatment also reduces the hydrologic impact of urbanization. Wastewater-treatment costs in the North China Plain

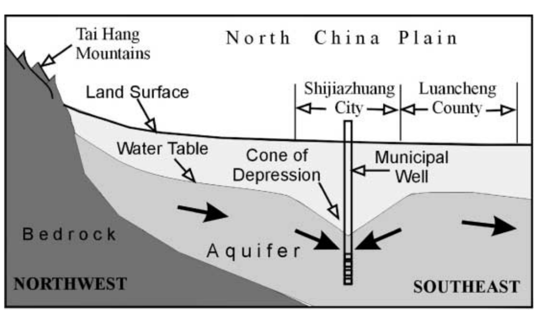

Fig. 6. Schematic cross section of the study area, illustrating groundwater concepts. Solid arrows indicate dominant groundwater flow directions. Diagram is not to scale.

are around 1 yuan/m^3 (Nyberg & Rozelle, 1999). The most effective way to reduce wastewater treatment costs is to improve urban water-use efficiency, thereby reducing the quantity of discharge needing treatment. Although urban water conservation measures and wastewater reuse are expensive propositions, Howitt (1998) found that, in California, either of these two measures would offer greater potential increases in water supply than agricultural water conservation, land fallowing, and surface storage construction combined, in terms of water-yield-to-cost ratios. Moreover, unlike irrigation efficiency, which has little impact on water-table declines, improving urban water-use efficiency decreases groundwater pumping without decreasing local recharge (because wastewater is typically discharged away from the city), and thus can reduce the size of the cone of depression. Already, Shijiazhuang has depleted two-thirds of its 60 m aquifer thickness (Liu *et al.*, 2001); continued depletion is not sustainable.

The scope for improving industrial water-use efficiency is considerable. Water use per industrial product is 3–10 times greater in China than in other industrialized countries (He, 1991; Zhang & Zhang, 1995; Brown & Halweil, 1998; World Bank, 2001). An exception is Tianjin (Figure 1), which increased its industrial water recycling rate from 40% in the 1980s to 74% in the 1990s by implementing industrial water conservation measures. As a result, from 1984 to 1994, Tianjin reduced its water withdrawals per yuan of industrial production by one third (Bai & Imura, 2001). Shijiazhuang City is currently attempting to implement its own industrial water-conservation measures. For every 10 million m^3/yr not pumped, the average rate of groundwater decline beneath Shijiazhuang City potentially could decrease about 20 cm/yr[4]. With an industrial pumping rate of 340 million m^3/yr (Shijiazhuang Water Conservation Bureau, issued annually), Shijiazhuang City can significantly reduce the size of its cone of depression by following Tianjin's lead.

The scope for reducing municipal (domestic) water use may be more limited than for industrial water use. Using 1997 data, the 99 million m^3/yr Shijiazhuang City pumps for domestic use[5] amounts to 183 liters per day (l/d) for each of the city's 1.48 million residents (Xinhuanet.com, 2002). This rate of domestic water use exceeds the minimum standard of 50 l/d necessary to meet basic drinking, sanitation, bathing and cooking needs (Gleick, 1996), but falls within the normal worldwide range of 40–200 l/d for these uses (Gleick *et al.*, 1995). By adopting water-conservation measures such as metering, rationing and upgrading household plumbing systems, water-stressed Tianjin maintained a relatively low per capita water use of about 128 l/d from 1984 to 1996. However, deliveries to household uses are expected to increase somewhat as household water supplies and sanitation facilities improve and plumbed household appliances gain popularity (Bai & Imura, 2001).

By treating and reusing urban wastewater for use in the urban and industrial sectors, urban water depletion could be greatly reduced, requiring fewer deliveries to cities. Careful consideration of the water demands of urban landscapes (low water-consuming native vegetation versus trees and turf) could reduce both delivery requirements and water consumption. Water-depleting industries can be moved off the North China Plain. Shijiazhuang City's water-consuming industries produce pharmaceuticals, fertilizers, and other chemicals; mill flour; brew beer; and dye textiles. Tianjin and Beijing have successfully altered their industrial structures to consume less water by encouraging water-thrifty

[4] Assumes a specific yield of 0.2 and a 250 km2 cone of depression.

[5] In 1997, Shijiazhuang City's wells pumped 439 million m3/yr (Liu *et al.*, 2001), of which industry used 340 million m3/yr (Shijiazhuang Water Conservation Bureau, 1949–1999), leaving 99 million m3/yr for domestic use.

industries such as metallurgical, automotive and electronics producers and discouraging water-consuming industries such as textile manufacturers. As a result, the ratio of water use to industrial production has decreased steadily in both cities since the mid-1980s (Bai & Imura, 2001).

The magnitude of the cone of depression beneath Shijiazhuang and other cities may be reduced through the management of wastewater flows. Instead of discharging wastewater outside of the urban area, many municipalities worldwide augment their water supplies by artificially recharging treated wastewater into underlying aquifers, through infiltration basins and injection wells (Commission on Geosciences Environment & Resources, 1994). If 100 million m^3/yr of wastewater were treated and artificially recharged, water levels beneath Shijiazhuang City potentially could rise 2 m/yr.

Granted, municipal wastewater already recharges aquifers in the North China Plain, so the regional impact of treating and artificially recharging wastewater could be considered only an improvement in groundwater and surface-water quality, rather than quantity. But groundwater contamination is itself a form of groundwater depletion when it cannot be safely reused by other uses – for example, if heavy metals get mixed into the groundwater supply. In essence, contaminated water is lost from the usable supply. In that sense, then, treating municipal wastewater would increase the overall supply, even at the regional scale.

Runoff from the impermeable roofs and paved roads in urban areas also can be captured and artificially recharged into underlying aquifers. Instead of discharging storm runoff as wastewater, Long Island, New York (population 2.7 million), uses more than 3,000 infiltration basins to artificially recharge at least as much water as received through precipitation under pre-development conditions (Seaburn & Aronson, 1974). Artificially recharging half of the 460 mm of annual precipitation could potentially raise the water table beneath Shijiazhuang City by 1.1 m/yr. If this practice were continued for a prolonged period, the cone of depression beneath the city would convert to a mound, restoring lateral groundwater flow to aquifers beneath Luancheng County.

4.2. Integrating urban land use into a balanced water budget

With no supplemental inflows (increased rainfall, inter-basin water transfers) to groundwater-irrigated areas, the water budget will balance only when evapotranspiration equals precipitation. Physically, groundwater pumping is not yet limited. For example, although water levels in Luancheng County have dropped 10–27 m already, they can still decrease another 40–90 m before exhausting the upper aquifer (Hebei Province Geology Team Number 9, 1980). Nowhere in the North China Plain has an aquifer completely dried up. Despite the increasing cost of pumping as the water table declines, this remaining groundwater reservoir can buy land-use planners the time to manage long-term, sustainable water use through logical planning, rather than by reacting to a crisis.

As explained above, changing cropping practices can reduce the rate of groundwater decline, but in itself is not capable of stabilizing the water table. Replacing agricultural landscapes with urban landscapes could reduce regional groundwater decline, but may present significant socio-political challenges. Of the proposed approaches, land fallowing – either year-round or throughout the winter-wheat season – offers the only means of alleviating groundwater declines, independent of other land-use changes. However, leaving land fallow contradicts China's deeply engrained goal of food self-sufficiency, and therefore would almost certainly meet stiff resistance from farmers to high-level policymakers (Shin, 1999). Nevertheless, crop changes and even periodic fallowing at a socially acceptable scale can play an important role, along with other, complementary approaches in assuring a sustainable future for agriculture.

Every landscape is a mosaic of different land uses with different evapotranspiration rates. The goal of achieving sustainable water use is to create a mosaic of land uses which, combined, deplete less water than is naturally replenished. For Luancheng County, this means reducing average evapotranspiration from about 66 to less than 46 cm/yr. Table 1 lists various land uses, along with the approximate rate at which each depletes water from the hydrologic system. For crops, estimated depletion is evapotranspiration as calculated by Kendy *et al.* (2004). For total fallow, estimated depletion is negligible, assuming all weeds are eliminated and almost all rainfall infiltrates. For urban land use, the actual depletion rate is not known. However, if we assume all wastewater is treated and knowing that urban water depletion is considerably less than depletion from irrigated land, a figure of one half the average evapotranspiration rate from cropland in Luancheng County, 33 cm/yr, is a conservative estimate. In fact, the actual urban depletion rate is likely much lower, and can be made lower still by altering industrial water-use practices.

An infinite number of land-use combinations exists which, combined, deplete only 46 cm/yr. Figure 7A and B illustrate several possibilities, based on the depletion rates listed in Table 1. Each figure shows three possible combinations of winter wheat/maize crop rotation, urban land use and total fallow. Each stacked bar shows a different combination of these land uses which, combined, deplete no more than 46 cm/yr.

Figure 7A assumes all cropland is devoted to the traditional winter-wheat and summer-maize rotation. From this figure, it can be seen that the more land becomes urbanized, the less land must be fallowed in order to arrest water-table declines. Due to the large area of fallowed land, the land-use combinations shown in Figure 7A may not gain acceptance in the North China Plain, where unused land is considered wasteful.

Figure 7B perhaps gives more politically palatable options. Instead of assuming traditional farming methods, the bottom graph assumes that all wheat and maize crops are either mulched or replaced with vegetables. Either scenario would reduce crop evapotranspiration by 10–11 cm/yr (Table 1). As a result, more land can be urbanized and less land needs to be fallowed for a given percentage of cropland.

The third stacked bar on Figure 7B represents 60% urban land use. If overall crop evapotranspiration were reduced by at least 10 cm/yr and urban water depletion were 33 cm/yr or less, Figure 7B suggests that water table beneath Luancheng County could stabilize under this scenario without fallowing any farmland.

Every landscape is a mosaic of land uses. In our example, we showed how a landscape consisting of 60% urban land use and no fallowed land could achieve a balanced water budget. Although this level of urban land use might be technically feasible, its political and economic acceptable are highly dubious. Even if the urban population reaches 60% as projected, urban land use is unlikely to increase proportionately. Currently, with a population that is about 40% urban, only about 10% of China's land use is urban. If rural-to-urban population migration continues as projected, urban land use will not increase to anywhere near the 60% we modeled. Moreover, the Chinese government has recently issued policies and regulations specifically to stem the tide of conversion from irrigated agricultural to urban land use. Drastic increases in urban land use would threaten China's food and environmental security. It is neither possible nor rational to urbanize 60% of the landscape.

It should be noted, however, that urban water consumption rates are likely much lower than the 33 cm/yr assumed in our analysis. Domestic consumption rates for drinking and washing are generally

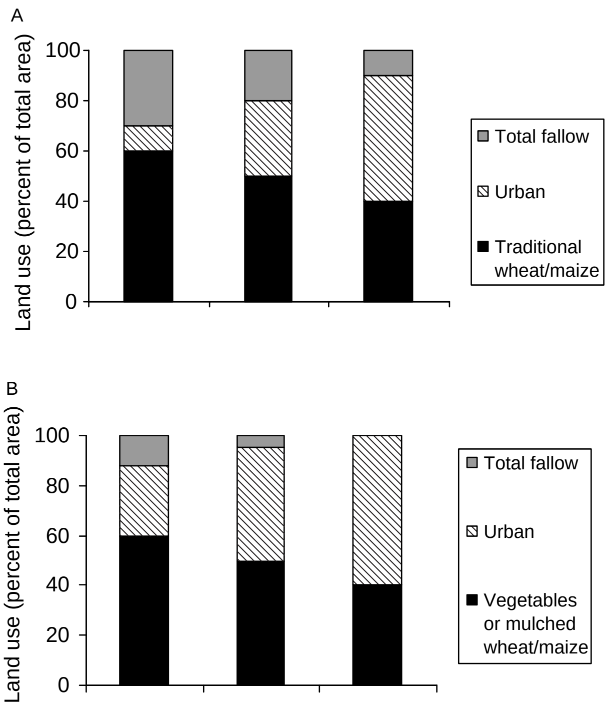

Fig. 7. Examples of land uses, which together deplete approximately 46 cm/yr of water. Each stacked bar represents a different combination of total fallow, urban, and irrigated agricultural land use. The estimated depletion rates for different land use categories are listed in Table 1. (A) Assumes cropland maintains traditional flood irrigated winter-wheat/summer-maize rotation system. (B) Assumes all wheat and maize is either mulched or replaced with vegetable crops, thereby reducing crop evapotranspiration by 10–11 cm/yr.

Table 1. Estimated annual water depletion rates associated with various land uses.

Land use	Depletion (cm/yr)	Notes and references
Cropland		
Winter fallow/summer millet	43	Crop evapotranspiration based on soil-water balance modeling (Kendy *et al.*, 2003a), using typical Luancheng County planting and harvest dates and 1971–2000 daily climate data.
Winter fallow/summer cotton	49	
Winter fallow/spring-fall vegetables	62	
Winter wheat/summer maize	73	
Winter wheat/summer sweet potato	74	
Mulched winter wheat/summer maize	63	Same as above. Water savings from You & Wang (1996).
Total fallow (rainfall harvesting)	0	Weed-free.
Urban	33	Assumes urban water depletion is half that of average Luancheng County cropland, 1971–2000.

less than 5% of withdrawals and may in fact be negative if large quantities of fluids are imported for drinking. Also, as discussed earlier, there is considerable scope for reducing industrial water consumption by improving processes and by relocating large water consumers off the North China Plain. Assuming lower urban water consumption rates, the water budget could balance with a lower proportion of urban land use than shown in Figure 7.

Although the numbers used to construct Figure 7 – especially urban water depletion – are imprecise, the approach represents a quantitative framework for collaborative land-use planning and long-term water management. Granted that: "...in most river basins, saving water is likely not the ultimate policy goal...the true policy goal [is] maximizing the social net benefits generated with limited water supplies" (Wichelns, 2002). This framework provides unambiguous hydrologic limits within which sustainable social development in the North China Plain can realistically be pursued.

Regarding the specific goals of sustainable development, however, it should be noted that although stabilizing water-table declines will preserve aquifers for human use, a full reversal of the declines is prerequisite for stream restoration. Until groundwater levels return to the elevations of stream channels, rivers and streams will continue to be deprived of ecologically critical baseflows. In the meantime, perhaps aquatic ecological restoration could be jump-started by managing treated wastewater discharges into stream channels to mimic a natural flow regime.

In addition to future land-use ratios, the physical layout of those land uses also is at issue. Whereas the World Bank (2001) recommends a few megacities, the Chinese leadership advocates many small cities (Fu, 2001; Gao, 2001). From a regional water-balance perspective, there should be no significant difference, so long as total depletion is the same. From a local perspective, however, the size of individual urban areas may need to be limited to prevent cones of depression from exceeding aquifer depths, at least until sufficient water-conservation measures are adopted to arrest groundwater declines. Another important consideration is the ability to fund, implement and regulate central wastewater treatment for one large city, compared to a large number of treatment systems dispersed among many small cities. Also, access to urban wastewater may help determine which rural areas will remain irrigation-dependent, which might revert to rainfed agriculture, and which will convert to potentially more lucrative industrial uses.

5. Concluding remarks

The current irrigated agricultural land use in the North China Plain is supported by unsustainable groundwater mining, as evidenced by a steadily falling water table, despite significant reductions in pumping. For the water table to stabilize, evapotranspiration (consumption or depletion, as distinguished from pumping, or use) must decrease. Of the various options evaluated – changing crops, fallowing land, adopting water-saving technology, increasing water prices, and urbanizing – the combination of urbanization, land fallowing, and implementing water-saving technology in both industry and agriculture is the only technically feasible option that can achieve the goal of arresting groundwater declines, and could potentially result in net groundwater replenishment.

Technical feasibility, however, is only one of many criteria for implementing new policies. Equally, if not more, important are political and economic acceptance. Given China's longstanding goal of food self-sufficiency and its tradition of maximizing land productivity, fallowing cropland is unlikely to gain political acceptance at any level, from local to national. Urbanization, on the other hand, is not only politically and economically acceptable, it appears to be inevitable. Nevertheless, while urbanization can bring about water equilibrium from a hydrological perspective, it is not clear from an economic perspective how the cost of water treatment or the loss in farm production will be compensated to underpin the equilibrium.

Withdrawing some land from irrigation is an essential requisite for achieving sustainable water use in the North China Plain. This finding counters the longstanding policy goal of continually increasing the irrigated area in order to achieve food self-sufficiency. Our hydrologic analysis suggests that fundamental changes in this policy are inescapable. Other analysts have also predicted that China will need to abandon its food self-sufficiency policy in favor of purchasing a significant proportion of its grain from the international market (e.g. Brown, 1995; Huang *et al.*, 1997) and that "...this 'virtual water import' option needs to be incorporated into the current regional and national agricultural development strategy in which crop structural adjustment is at the core" (Yang & Zehnder, 2001). A major challenge then, will be to introduce socially, politically, and economically acceptable incentives to reduce the irrigated area. Urbanization meets all of these criteria.

Urbanization can help reduce competition for water between sectors while still allowing for economic growth if: (1) both the industrial and agricultural sectors adopt water-saving technologies and (2) urban wastewater and runoff are treated and reused directly in agriculture or indirectly through artificial recharge. Combined, the two conditions must result in a net decrease in water consumption at the regional scale. Both of these conditions are technically feasible and achievable. More scope exists for meaningful water savings for municipal/industrial use than for agricultural use. However, by conserving and reusing water in both sectors, a landscape mosaic of urban and irrigated agricultural areas potentially can coexist without depleting limited water resources on the North China Plain.

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