

COMBINING URBAN AND RURAL WATER USE FOR A SUSTAINABLE NORTH CHINA PLAIN

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Abstract

Competing demands on limited water resources have resulted in persistent water shortages for the North China Plain. Despite years of effort to mitigate the problem, ground-water levels continue to decline steadily. A quantitative analysis of hydrologic changes affecting Luancheng County, Hebei Province, from 1949 to 2000 identifies crop evapotranspiration as the root cause of water-table declines beneath this ground-water irrigated area.

Potential evapotranspiration greatly exceeds precipitation in the North China Plain. For centuries, farmers raised 2-3 rainfed crops every two years. By not using irrigation, the quantity of water taken up by crops was limited by -- and could not exceed -- precipitation. It was not until the proliferation of mechanized wells in the 1960s that farmers could consistently produce 2 crops every year. From the 1970s to the present, actual evapotranspiration from irrigated cropland in Luancheng County has remained constant at about 66 cm/y, compared to an average of about 46 cm/y of rainfall. Ground-water mining provides the additional 20 cm/y to meet crop water requirements, but also depresses the water table about 1 m/y beneath Luancheng County.

Attempts to make water use sustainable have centered on improving irrigation efficiency to reduce ground-water pumping. Indeed, pumping rates have decreased about 50 percent since the 1970s. However, ground-water recharge from excess irrigation has decreased correspondingly. Therefore, water-table declines have continued unabated. Because irrigated areas overlie the shallow aquifer, excess irrigation water always replenishes the water supply. In this physical configuration, irrigation efficiency improvements save no water. The only way to save water is to reduce evapotranspiration, which can be accomplished by reducing the cropped area.

Government leaders are currently promoting rapid urbanization of the North China Plain as a means to stimulate economic growth, absorb the rural labor surplus, and reduce the income disparity between rural and urban workers. From a hydrologic standpoint, is urban land use a viable alternative to irrigated cropland? Like agricultural areas, most cities on the North China Plain rely on ground water. However, unlike irrigated fields, water that passes through industrial and domestic users does not necessarily recharge the underlying aquifer. Rather, most wastewater discharges to rural areas outside the cities. Likewise, rainfall that lands on impermeable urban surfaces quickly drains away from cities. Therefore, although evaporation from urban areas is less than from cropland, water-table declines beneath cities are even more severe than beneath cropland. The major hydrologic impacts of urbanization, then, are localized displacement – but not necessarily consumption – and contamination of water.

By replacing some cropland with urban areas, regional evapotranspiration would likely decrease. Then the problem would reduce to prudent management and distribution of urban water resources. Municipal wastewater treatment could transform a disposal problem into a water-resource solution, to be utilized by downstream irrigators. There appears to be considerable scope for improving industrial water-use efficiency, which would reduce potential costs of both ground-water pumping and wastewater treatment. Capturing and artificially recharging storm runoff into underlying aquifers could further alleviate ground-water declines beneath urban and nearby areas. Thus, replacing rural with urban land use potentially could benefit the North China Plain hydrologically, provided urban runoff and wastewater quality improve.

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Introduction

Water is the most vital and limiting resource in the North China Plain (Brown and Halweil, 1998; Chen and Ma, 1998; Liu and Wei, 1989; Ren, 1992; World Bank, 2001). Virtually all clean surface water is diverted into cities for municipal use, leaving industries and agriculture to compete over a diminishing ground-water resource, even as production continues to increase. Consequently, natural streamflow has almost completely ceased, the depth to ground water is declining steadily, salt water is intruding into previously fresh-water aquifers, and in some places the land surface is subsiding. The irrigation water shortage alone is estimated to be 1.6 billion m³/year (Liu et al., 2001).

The unsustainable nature of ground-water development in the North China Plain has been recognized since the 1970s, when long-term, widespread water-table declines first were documented (Zhu and Zheng, 1983). However, years of effort to reverse the declines have had no effect. In this paper, we identify crop evapotranspiration as the single, root cause of ground-water depletion, and explain why past efforts to save water have failed to reverse ground-water declines. Based on this finding, we introduce a systematic approach to achieving sustainable water use through land-use changes, including urbanization. This research is based on data, maps, and reports obtained in Shijiazhuang City and Luancheng County, Hebei Province, in 2001. Interviews with farmers, researchers, and city, county, and provincial government officials added invaluable insight.

Historical Water Use in Luancheng County

Located at latitude 38 degrees north and an elevation of 45-70 m above sea level, Luancheng County, Hebei Province (fig. 1) provides a natural laboratory for assessing hydrologic impacts of historical water use on the North China Plain. The 397-km², rural county is downstream from three over-allocated rivers and adjacent to Shijiazhuang City, the provincial capitol. Typical of the North China Plain, the availability and seasonal distribution of water are the factors most limiting agricultural production. Most of the 461 mm of rainfall occurs during the humid summer months, with very little falling during the spring and autumn, and even less during the cold, dry winters (Luancheng County Meteorological Bureau, unpublished data, 1971-2000).

Therefore, reliable crop production depends on ground-water irrigation. The unconfined alluvial aquifer that supplies ground water to Luancheng County consists of sand, silt, and clay, and increases in thickness from about 200 m in the west to about 370 m in the east (Luancheng County Natural Resources Survey Investigation Team, 1980). Due to its location near the western edge of the Plain, this aquifer is relatively permeable, producing among the highest well yields in the region (Hebei Province Department of Geology and Mineralogy, 1992).

Hydrologically, Luancheng County typifies most, but not all of the North China Plain. Specifically, the county represents only those places that obtain water from shallow, unconfined aquifers. In contrast, many coastal and some urban areas use deeper, confined aquifers, which lack direct hydraulic connections to the land surface.



Figure 1. Location of Luancheng County and the North China Plain.

Ground-water pumping is a relatively new technology. For hundreds of years prior to ground-water development, rainfed cotton, millet, sorghum, and sweet potato—all summer crops—were the primary products of Luancheng County. At most, three crops could be grown every two years (Luancheng County Chronicle Compilation Committee, 1995).

It was not until the 1960s that government technical and financial infusions facilitated the rapid proliferation of drilled, mechanized wells (Luancheng County Chronicle Compilation Committee, 1995), enabling continuous cropping with 2 harvests every year (Dong, 1991). Although water-table declines were evident, Luancheng County was hailed as a "Model County" for increasing crop yields through ground-water irrigation (Luancheng County Chronicle Compilation Committee, 1995).

Like all means of production, ground water was managed collectively. Most wells drilled in Luancheng County in the 1960s and 1970s were large-capacity ($100 \text{ m}^3/\text{hr}$), shallow wells less than 20 m deep (Kendy et al, 2003d). Earth-lined ditches conveyed water from wells to communal fields. Water-transit losses were about 60 percent (Cao and Zhang, 1994). With well drilling, electrical power, and water all subsidized, brigade leaders ordered and enforced irrigation 24 hours per day (Kendy et al, 2003d).

Production in Luancheng County decollectivized from communes to households in 1979-82. By then, regional water-table declines had become incessant (Zhu and Zheng, 1983). The coincidence of ground-water depletion with the economic reforms fundamentally changed ground-water management (Wang and Huang, 2002). As each shallow, communal well was retired, several deeper ($\sim 60\text{-}70 \text{ m}$), lower-capacity ($40 \text{ m}^3/\text{hr}$), family-operated wells replaced it (Kendy et al, 2003d). With wells now located closer to the fields they irrigated, delivery efficiency improved and irrigation times were reduced (Kendy et al, 2003d). Ground-water pumping for irrigation decreased from about 102 cm/y in 1976 to about 39 cm/y in 1996 (fig. 2), with no losses in crop yield.

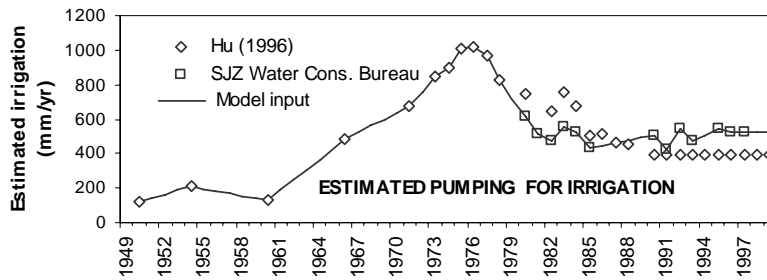


Figure 2. Ground-water pumping for irrigation in Luancheng County, 1949-99. Irrigation estimates are by Hu (1996 and oral communication) and the Shijiazhuang Water Conservation Bureau (issued annually). “Pumping” in the 1950s was primarily hauling, rather than pumping, from shallow, brick-lined wells. “Model input” indicates ground-water pumping and irrigation values used to calculate annual water balances (Kendy et al., 2003b, 2003c).

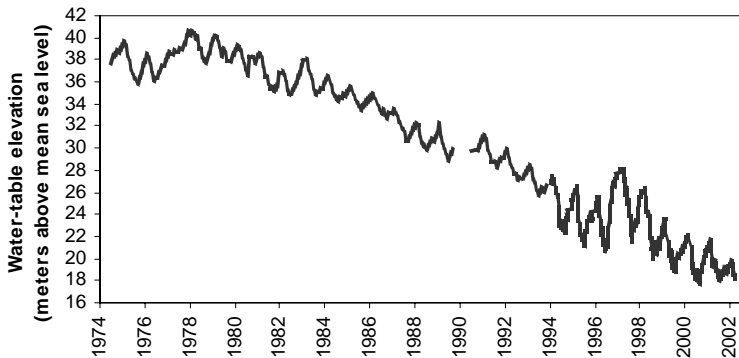


Figure 3. Hydrograph showing historical water-table elevations beneath Luancheng Agro-Ecological Research Station (Chinese Academy of Sciences), Luancheng County, Hebei Province, 1974-2000. Land-surface elevation is 50.27 meters above mean sea level.

In the late 1990s, the area devoted to cash crops such as melons, turf, and vegetables began to increase rapidly. As a “National Demonstration County” for water saving, Luancheng County benefits from a cost-share program in which the provincial, prefecture, and county governments and the farmer contribute 30, 30, 30, and 10 percent, respectively, to greenhouses, sprinklers, drip and micro-irrigation, and underground PVC and concrete pipes. These water-saving technologies are being phased in with many of the new cash crops (Kendy et al., 2003d), thus further reducing ground-water pumping requirements.

WATER-BALANCE ANALYSIS

Although ground-water withdrawals have decreased by more than half since their peak in the 1970s (fig. 2), water-table declines have remained steady at nearly 1 m/y (fig. 3). Clearly, vast improvements in irrigation efficiency have significantly reduced pumping, yet have done nothing to stabilize the water table. A comprehensive water-balance analysis of the aquifer beneath Luancheng County from 1949 to 2000 (Kendy et al, 2003a, 2003b, 2003c) explains the apparent contradiction.

Figure 4 shows schematically how the water balance of Luancheng County has changed over time as the irrigated area has grown. The ground-water budget indicates that lateral inflows balance lateral outflows (Kendy et al, 2003c), so only precipitation and evapotranspiration are shown in the figure. Average annual precipitation has decreased from about 54 cm/y in 1955-80 to about 46 cm/y in 1971-2000 (Luancheng County Meteorological Bureau, unpublished data). Evapotranspiration, meanwhile, has greatly increased, from about 46 cm/y when farmers grew only one rainfed crop every year to an average of 66 cm/y under the current, irrigated two-crop-per-year system (Kendy et al., 2003b). Thus, although potential evapotranspiration has not changed, actual evapotranspiration has increased substantially. Before irrigation development and during the early years of small-scale irrigation, precipitation exceeded evapotranspiration. Excess water recharged the underlying aquifer and at times even filled it 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 precipitation and evapotranspiration. That additional water comes from ground-water mining. The quantity mined, 20 cm/y, fully accounts for the observed water-table declines (Kendy et al, 2003b).⁴

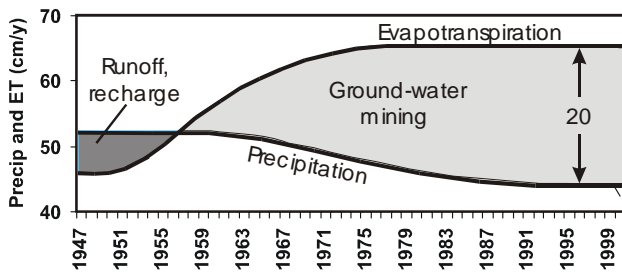


Figure 4. General relationship between precipitation and evapotranspiration for cropland in Luancheng County, 1947-2000. Actual evapotranspiration has increased over time as the area and duration of irrigated cropping have grown.

Therefore, it is critical to distinguish between water that is pumped from the aquifer and water that is actually depleted from the hydrologic system. Evapotranspiration is the only water actually depleted from the system. The crops cannot consume any ground-water withdrawals in excess of 66 cm/y. Instead, this excess irrigation water drains through the soil profile, eventually recharging the aquifer, and is therefore retained in the hydrologic system. Thus, as long as all crop-water requirements are met, every reduction in pumping triggers an equal reduction in ground-water recharge from irrigation drainage. Depletion from the hydrologic system remains steady at about 20 cm/y, and the net impact of pumping reductions on water-table declines is nil.

By analyzing the water-balance, we have shown that aboveground depletion rates are key to sustainable ground-water pumping (Kendy, 2003c). The only means to reduce the rate of ground-water declines beneath irrigated cropland in Luancheng County and the North China Plain is to reduce crop evapotranspiration. Thus, sustainable ground-water use begins not with reducing irrigation pumping per hectare, but rather with reducing the total area of irrigated land.

⁴ Assumes a specific yield (S_y) of 0.2 (Lin and Yang, 1991). Dimensionless S_y may be thought of as the aquifer porosity. If $S_y = 0.2$, or 20%, then 20 percent of any aquifer volume contains water, and the other 80 percent contains geologic material (in this case, sand, silt, and clay). Thus, for every 20 cm of water removed, the water table actually declines $0.2 \text{ m}/0.2 = 1.0 \text{ m}$.

Balancing the Water Budget: Options for a Sustainable Future

Ground-water declines will slow only when water depletion decreases, either by increasing inflows or by decreasing outflows. Here, we discuss several proposed water-saving options with respect to their potential impacts on the water balance.

Nanshui Beidiao, the engineering scheme to transfer water from the Yangze River north to the North China Plain, will increase inflows. However, total inflows will be much less than needed to meet the regional deficit between precipitation and evapotranspiration. Moreover, water deliveries will be targeted primarily to cities, not to irrigated cropland (Liu, 1998; Liu and You, 1994; Nyberg and Rozelle, 1999). *Nanshui Beidiao* will provide a critical water supplement to some local areas, but is no solution to regional ground-water declines.

Low-pressure, underground pipelines are rapidly replacing open irrigation ditches across the Plain (Nyberg and Rozelle, 1999). Water managers favor the underground pipes because they reduce evaporation from the water surface. Farmers favor the underground pipes because they replace aboveground ditches, thus increasing the area available for cultivation (Kendy, 2003d). However, these 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 now evapotranspire from the entire root depth throughout the growing season.

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 likely increases evaporation compared to traditional flood irrigation.

Evaporation reduction can actually decrease outflow from the overall hydrologic system, and therefore can save water. However, the scope for reducing evaporation is relatively small because plantings are densely spaced 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 and Wang, 1996) to 13.5 cm/y (Zhang Y.Q., Shijiazhuang Institute of Agricultural Modernization, written commun., 2002) in the North China Plain without decreasing productivity. Greenhouses also may save water because their artificially humid, windless environment reduces evaporation (Albright, 2002).

Water price increases encourage conservation (Anderson and Leal, 2001; Lampton, 1983; Nyberg and Rozelle, 1999; Zhang and Zhang, 1995), but would not necessarily benefit the North China Plain. Consumers' initial response to a commodity price increase usually is to reduce consumption of that commodity. In the case of irrigation water, farmers are likely to reduce pumping. However, as we have shown, seepage reductions concomitant with pumping reductions result in no net change in ground-water depletion rates. Therefore, water price increases would only impose undue financial burdens on farmers without solving the intended problem. Only if water pricing is used to encourage land-use change might higher prices be justified. In the past, farmers had no choice but to continue farming in order to meet grain quotas. However, recent abolishment of quotas might provide opportunity for water pricing to stimulate a needed reduction in the irrigated area (Nyberg and Rozelle, 1999).

Crop changes to less water-intensive systems than the popular winter wheat/summer maize rotation (Nyberg and Rozelle, 1999; Yu, 1995; Yang and Zehnder, 2001) can significantly reduce outflows from the hydrologic system only if no winter crop is grown, regardless of the summer crop type (Kendy et al, 2003b). The amount of water saved depends primarily on the length of the crop growing season (Kendy et al., 2003a, 2003b). For example, if Luancheng County had produced only cotton and millet since 1962, then the water table would have remained stable (fig. 5). Vegetables, which comprise early- and late-season crops grown consecutively on the same land, deplete more water than other summer crops due to their longer combined growing season. Thus, of the proposed crop changes analyzed, the reintroduction of annual winter fallow offers the only means of alleviating ground-water declines, independent of other land-use changes.

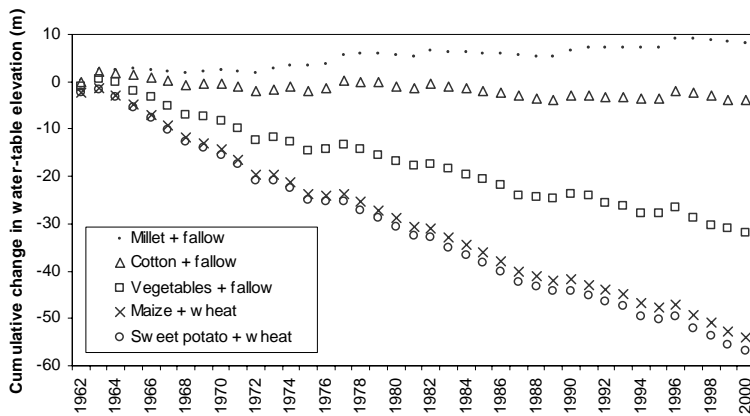
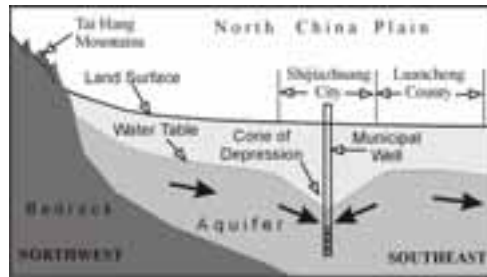


Figure 5. Estimated ground-water declines that would have resulted from five different crop combinations under typical irrigation practices, given historical climate conditions in Luancheng County, 1962-2000 (Kendy et al., 2003b).

Urbanization and industrialization of rural North China are being promoted to employ a growing rural labor surplus and to narrow the income disparity between urban and rural residents (Fu, 2001; Gao, 2001). In the process, even more of the agricultural water supply would be diverted to fulfill the needs of the expanding urban industrial sector, where its marginal value is higher. While the social and economic benefits of urbanization have been argued and analyzed extensively, the hydrologic impacts have not. Again taking a water-balance perspective, we can gain valuable insight into potential hydrologic impacts of converting from agricultural to urban land use.

Proximity to large urban areas markedly influences local hydrology. Urban land surfaces tend to be impermeable. Therefore, precipitation runs off, rather than recharging the aquifer underlying the city. Overpumping ground water 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 many cases extends laterally far beyond city limits (fig. 6). Thus, ground water beneath urban areas 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 position in the regional flow path (fig. 6). Additional impacts result from urban runoff and wastewater, which discharge onto adjacent farmland, where they may be used for irrigation.

Figure 6. Schematic cross section of Luancheng County and Shijiazhuang City, illustrating hydrogeologic impacts of concentrated municipal well pumping. Solid arrows indicate dominant ground-water flow direction. Diagram is not to scale.



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. Likewise, in many industrial uses, a small fraction delivered to the industry is evaporated, but drainage flows could be highly polluted. Treatment of wastewater flows is imperative for healthy water systems. By treating wastewater, the main hydrologic impact of urbanization would reduce to local displacement, but not depletion, of water.

The most effective way to reduce wastewater treatment costs is to improve urban water-use efficiency, thereby reducing the quantity of discharge needing treatment. Unlike irrigation efficiency, which has little impact on water-table declines, improving urban water-use efficiency decreases ground-water pumping without decreasing local recharge, and thus can reduce the size of the cone of depression. Although domestic water-use efficiency is unlikely to improve significantly, the scope for improving industrial water-use efficiency is considerable (Kendy, 2003d).

Only by increasing recharge to equal discharge can local water-table declines be arrested. Thus, even with maximized urban water-use efficiency, urban cones of depression will persist as long as cities continue to discharge wastewater and storm runoff outside their city limits. Thus, eliminating depression cones beneath urban areas depends on managing wastewater flows. Instead of discharging wastewater, many municipalities worldwide augment their water supplies by artificially recharging storm runoff and treated wastewater into underlying aquifers through infiltration basins and injection wells (Commission on Geosciences Environment and Resources, 1994). Likewise, runoff from the impermeable roofs and paved roads of urban areas also can be captured and artificially recharged into underlying aquifers. If 100 million m³/y of wastewater were treated and artificially recharged, then water levels beneath Shijiazhuang potentially could rise 2 m/y. Artificially recharging 46 cm/y of precipitation potentially could raise the water table beneath Shijiazhuang by 2.3 m/y. Continued for many years, the cone of depression beneath the city would convert to a mound, causing lateral subsurface flow to once again recharge aquifers beneath Luancheng County.

From a hydrologic standpoint, then, is urban land use a viable alternative to changing practices in irrigated cropland? Ultimately, the rate of regional ground-water decline will depend on how much water is evaporated. If, as is commonly assumed, urban land use depletes less water than crop evapotranspiration (Gleick, 2002), then replacing rural with urban land use potentially could benefit the North China Plain hydrologically, provided urban runoff and wastewater are treated.

Putting It All Together: Rational Land-Use Planning for the Future

Every landscape is a mosaic of different land uses. The goal of achieving sustainable water use is to create a mosaic of land uses which, combined, deplete less water than is naturally recharged. For Luancheng County, this means reducing evapotranspiration from about 66 to 46 cm/y. Table 1 lists various land uses discussed above, along with the approximate rate at which each depletes water from the hydrologic system.

Comment:

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

Land Use	Depletion (cm/y)	Notes and references
Cropland		
Winter fallow/summer millet	43	Based on soil-water balance modeling (Kendy et al., 2003b), 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	
Total fallow (rainfall harvesting)	0	Weed-free. All precipitation infiltrates.
Urban	33	Arbitrarily assumes urban water depletion is half that of average Luancheng County cropland, 1971-2000.

An infinite number of land-use combinations exist which, combined, deplete 46 cm/y. Figure 7 illustrates several possibilities, based on the depletion rates listed in table 1. Each graph 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, depletes 46 cm/y.

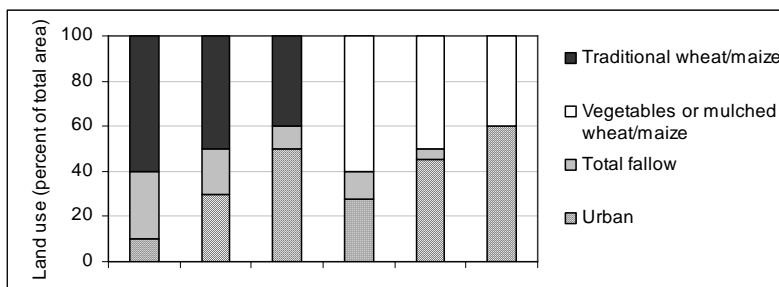


Figure 7. Six examples of land-uses which, combined, deplete approximately 46 cm/y.

The three stacked bars on the left assume all cropland is devoted to the traditional winter wheat and summer maize rotation. The graph shows 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, these land-use combinations may not gain acceptance in the North China Plain, where unused land is considered wasteful.

The three combinations depicted on the right (fig. 7) represent some perhaps more socially acceptable options. Instead of assuming traditional farming methods, the bottom graph assumes that all wheat and maize are either mulched or replaced with vegetables. Either scenario would reduce crop evapotranspiration by 10-11 cm/y (table 1). As a result, more land could be urbanized and less land would need to be fallowed for a given percentage of cropland.

Although the numbers used to construct figure 7 – especially urban water depletion – are imprecise, the approach provides a quantitative framework for integrated land-use planning and long-term water management. This framework provides unambiguous hydrologic limits within which sustainable social development in the North China Plain realistically can be pursued.

Conclusions

Past attempts to make water use sustainable have centered on improving irrigation efficiency to reduce ground-water pumping. Indeed, pumping rates for irrigation in Luancheng County have decreased by more than 50 percent since the 1970s. But ground-water recharge from excess irrigation has decreased equally. As a result, water-table declines have continued unabated. Because irrigated areas overlie the shallow aquifer, any excess irrigation water always replenishes the water supply. In this physical configuration, irrigation efficiency improvements save no water.

By considering the entire hydrologic system, we have shown that evapotranspiration is the only water actually depleted from the system. The only way to save water is to reduce evapotranspiration, which can be accomplished by reducing the cropped area. Thus, an eventual shift from irrigation to other, less consumptive water uses must play a crucial role in any long-term solution to water-table declines. Whether urbanization is part of that solution depends on whether urban and rural water can successfully be managed comprehensively, with net depletion rates no greater than natural replenishment rates. Urban wastewater treatment is critical to achieving this goal.

The inevitable conclusion of this analysis is that withdrawing some land from irrigation is an essential requisite for achieving sustainable water use in the North China Plain. This judgement counters the long-standing, successfully implemented policy goal of continually increasing the irrigated area. Our hydrologic analysis suggests that fundamental changes in this policy are inevitable.

Acknowledgements

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