RESEARCH REPORT

71

Policies Drain the North China Plain

Agricultural Policy and Groundwater Depletion in Luancheng County, 1949-2000

Eloise Kendy, David J. Molden, Tammo S. Steenhuis, Changming Liu and Jinxia Wang

International Water Management Institute

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IWMI receives its principal funding from 58 governments, private foundations, and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR). Support is also given by the Governments of Ghana, Pakistan, South Africa, Sri Lanka and Thailand.

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Acknowledgements: Funding for this research was provided by the Teresa and H. John Heinz III Foundation; the International Water Management Institute (IWMI); U.S. Department of Education Graduate Assistance in Areas of National Need (GAANN) Fellowship Program; Cornell International Institute for Food, Agriculture and Development (CIIFAD); and Cornell East Asia Program. IWMI and the Shijiazhuang Institute of Agricultural Modernization (SIAM), Chinese Academy of Sciences (CAS) provided technical and logistical support. The authors also acknowledge the support of the Comprehensive Assessment of Water Management in Agriculture and the Agricultural Water-Saving Foundation, Hebei Province of China, No. 01220703D. Thanks to Ludmilla Aristilde of Cornell University for providing mapping and drafting assistance. The authors extend their gratitutde to Larry M. Cathles and Max J. Pfeffer of Cornell University and Randy Barker of IWMI for many inspiring and insightful discussions, which greatly enhanced the quality of this work. Special appreciation is extended to Zeng Jianghai, Ma Qijun, Lin Yong, Jia Jinsheng, Zhang Qiuying, Li Fadong, Wang Yanmei, and Mao Xuesen of SIAM; Wang Guiling of the Chinese Land Resources Department, for assistance in obtaining and understanding historical information, without which this project would not have been possible.

Kendy, E.; Molden, D. J.; Steenhuis, T. S.; Liu, C.M.; Wang, J. 2003. *Policies drain the North China Plain: Agricultural policy and groundwater depletion in Luancheng County, 1949-2000*. Research Report 71. Colombo, Sri Lanka: International Water Management Institute.

/agricultural production / groundwater / aquifers / water shortage / irrigation efficiency / irrigation water / agricultural policy / crop production / economic growth / natural resources / water distribution / wastewater / water resources development / water management / water supply / hydrology / economic development / water scarcity / groundwater irrigation / wells / rivers / farming / crop yield / cotton / wheat / sprinkler irrigation / water conservation / water use efficiency / pumping / water balance / vegetables / hydroelectric schemes / rural economy / land use / irrigated farming / water policy / water demand / China/

ISBN 92-9090-517-4

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Contents

Summary

The North China Plain, 320,000 km^2 in extent, is China's most important center of agricultural production and home to more than 200 million people. Through extensive irrigation, the region produces more than 50 percent of the nation's wheat and 33 percent of its maize, making it critical to national food self-sufficiency. Yet, on the North China Plain, water is the most vital and limiting resource. Natural streamflow has almost completely ceased because of diversions to urban, industrial and agricultural uses. Groundwater levels are declining steadily, salt water is intruding into previously freshwater aquifers and in some places the land surface is subsiding. Even the largest cities, which receive highest priority for water distribution, endure repeated "crises" set off by water shortages.

The report examines the relationships between agricultural policies in the North China Plain, the approaches to water management that evolved from them, the quantity of water that was actually used, and the consequent groundwater depletion beneath Luancheng County, Hebei Province, from 1949 to 2000. To systematically address these relationships, we use a comprehensive water-balance approach. Our results indicate that a single, longstanding policy—that of using groundwater to meet the crop-water requirements not supplied by precipitation—is responsible for the steady rate of groundwater decline.

Attempts to make water use sustainable have centered on improving irrigation efficiency to reduce groundwater pumping. Indeed, pumping rates for irrigation in Luancheng County have decreased more than 50 percent since the 1970s. However, water-table declines have continued unabated. This is because the only significant inflows and outflows to and from this hydrologic system are precipitation and crop evapotranspiration, respectively. As long as the irrigated area remains unchanged, crop evapotranspiration remains constant. In Luancheng County, irrigated areas overlie the shallow aquifer, so any excess irrigation water supplied by groundwater pumping passes through the soil profile and replenishes the water supply. Thus, decreased pumping causes a corresponding decrease in groundwater recharge from excess irrigation, while precipitation and crop evapotranspiration remain unchanged. In this physical configuration, irrigation efficiency improvements save no water.

We explore various proposals to stabilize water levels, including crop changes, water-saving technology, and urbanization. Integrating these proposals, we present a quantitative framework for collaborative land-use planning and long-term, sustainable water management, again using a water-balance approach. 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 finding counters China's longstanding and successfully implemented policy of continually increasing the irrigated area in order to achieve the key societal objective of food self-sufficiency. The report is based on data, maps, reports, and interviews obtained in Shijiazhuang City and Luancheng County, Hebei Province, People's Republic of China in 2001.

Policies Drain the North China Plain: Agricultural Policy and Groundwater Depletion in Luancheng County, 1949-2000

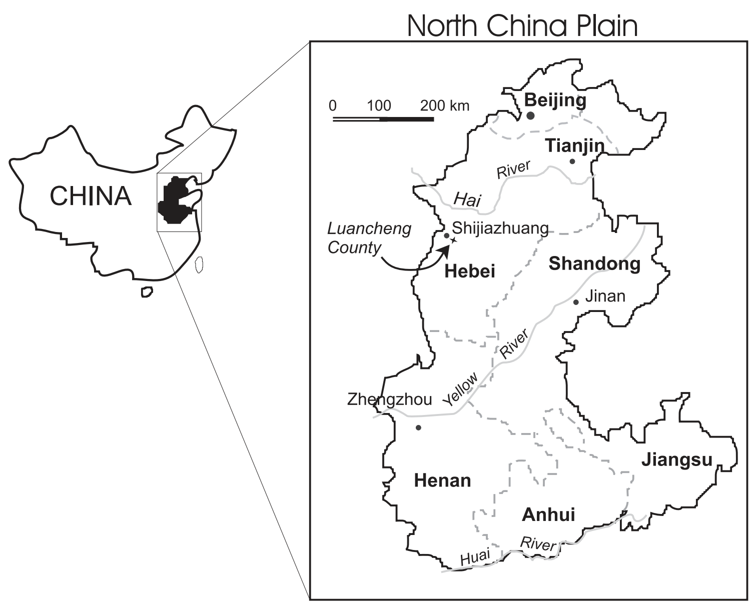
Eloise Kendy, David J. Molden, Tammo S. Steenhuis, Changming Liu and Jinxia Wang

Introduction

The North China Plain (figure 1) is China's most important center of agricultural production and home to more than 200 million people. It produces more than 50 percent of the nation's wheat and 33 percent of its maize (State Statistics Bureau 1999), and is therefore critical to achieving national food self-sufficiency, which, for 50 years, has been the central goal of China's agricultural policy (Huang 1998a). In recent years, extensive industrial development has contributed even more than crop production to rural economic output, and the resulting increase in local incomes has further spurred economic growth. Although primarily a rural area, about 20 percent of the population in the North China Plain resides in urban areas (Liu et al. 2001). The North China Plain also is home to the nation's capital, Beijing, and its sister port city Tianjin, the largest industrial center in northern China.

Economic growth throughout the region has accelerated to unprecedented levels, helping propel China to its current standing as a major international economic force. Since achieving this newfound prosperity, poverty levels throughout the country have dropped sharply, and extreme poverty has nearly been eradicated (State Council Information Office 2001).

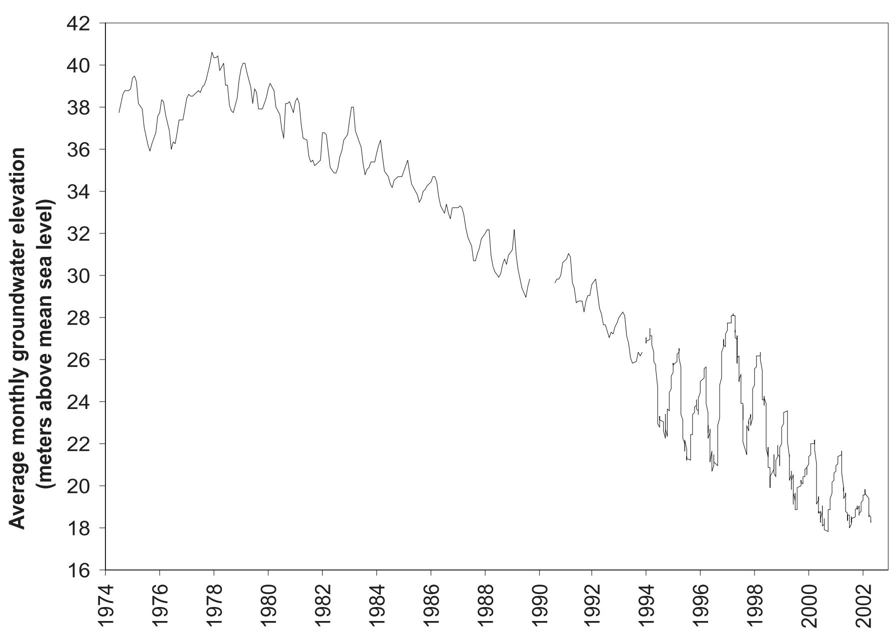
FIGURE 1.
Location of Luancheng County within the North China Plain.



However, these impressive social and economic gains were achieved with substantial costs. Natural resources provide the fuel for development, and the natural environment has become the receptacle for the waste products generated by development. In the North China Plain, water is the most vital and limiting resource (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 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 some places the land surface is subsiding. The irrigation water shortage alone is estimated to be 1.6 billion m^3/year (Liu et al. 2001). Even the largest cities, which receive highest priority for water distribution, undergo repeated "crises" set off by water shortages. Severe pollution—primarily from untreated industrial and municipal 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 (Ma and Ortolano 2000; Zhou 1995).

The unsustainable nature of water-resource development in the North China Plain has long been recognized. Teams of hydrologists were mobilized to study the problem, and then to quantify sustainable groundwater withdrawal rates as early as the 1970s, when long-term,

FIGURE 2.
Hydrograph depicting water-table elevations beneath Luancheng Agro-Ecological Research Station (Chinese Academy of Sciences), Luancheng County, Hebei Province, 1974-2002.



Note: Land-surface elevation is 50.27 m above mean sea level.

widespread water-table declines first became apparent (Zhu and Zheng 1983). Thereafter, each province has annually calculated and reported the increasing gap between its groundwater extraction and replenishment rates (e.g., Hebei Province Bureau of Water Resources 1949-1999).

Policy analysts have responded by identifying national agricultural, economic, environmental, and technical policies and institutions that have affected water management (Ash 1988; Brown and Halweil 1998; Crook and Diao 2000; He 1991; Huang 1998a; Kang and Yong 1998; Lampton 1983; Nickum 1998; Nyberg and Rozelle 1999). From these analyses logical policy recommendations have emerged, many of which have been implemented over the years. Most recently, the World Bank (2001) and others (Lohmar et al. 2003; Wang et al. 2001; Ye 1992; Zhang and Zhang 1995) have suggested shifting water from lower to higher marginal-value uses, importing water from the Yangze River, improving irrigation and industrial water-use efficiency, treating and reusing wastewater, privatizing water management, strengthening water rights and increasing water prices.

These proposals are only the latest in a longstanding cycle of policy analyses and recommendations. Yet, through every cycle, the water situation has continued to deteriorate (Ministry of Water Resources Bureau 1949-1999). Many observers blame lax enforcement of water-conservation and environmental-protection laws (He 1991; Ma and Ortolano 2000; Palmer 1998). While it is true that some good policies have failed to be fully implemented, it is just as true that other policies have not only been implemented, but have clearly influenced water use. But until now, there has been no effort to systematically associate causative policies with consequent impacts, especially at the local level, where the impacts are felt the most (Lohmar et al. 2003).

At this vital juncture, when "the deficit between water supply and demands has become the main constraint to further socio-economic development" (Chen and Ma 1998), a critical analysis of the hydrologic impacts of past policies is both timely and prudent. To recognize the links between policy and hydrology is to ensure that future plans address the underlying causes, and not just palpable symptoms of water scarcity.

This report examines the relationships between agricultural policies in the North China Plain, the approaches to water management that evolved from them, the quantity of water that was actually used and the consequent groundwater depletion beneath Luancheng County, Hebei Province, from 1949 to 2000. To systematically address these relationships, we use a water-balance approach. We identify a single, root cause for groundwater depletion—that of using groundwater to meet the crop-water requirements not supplied by precipitation—which explains why past policies to save water have failed to reverse groundwater declines. Finally, we discuss various proposed approaches to make water use in the North China Plain sustainable, again using a water-balance approach. Although pollution plainly impacts groundwater resources at least as seriously as overdrafts, this report 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 report focuses primarily on the hydrologic aspect. We hope to contribute a sound scientific basis to the overall, interdisciplinary quest for sustainability. 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 insights.

The Physical Environment

North China Plain

The North China Plain (figure 1) was ancient China's political, economic and cultural center, and the setting for countless events of great historical importance. Bordered by mountains on the west and the Yellow Sea on the east, the North China Plain (also known as the Huang-Huai-Hai Plain) is drained by the Huai River in the south, the Huang (Yellow) River in the center, and the Hai River in the north. With an average topographic gradient of about 1 percent, all three river basins slope almost imperceptibly from west to east. Three-quarters of the North China Plain has an elevation of less than 100 m above sea level (Yang 1991).

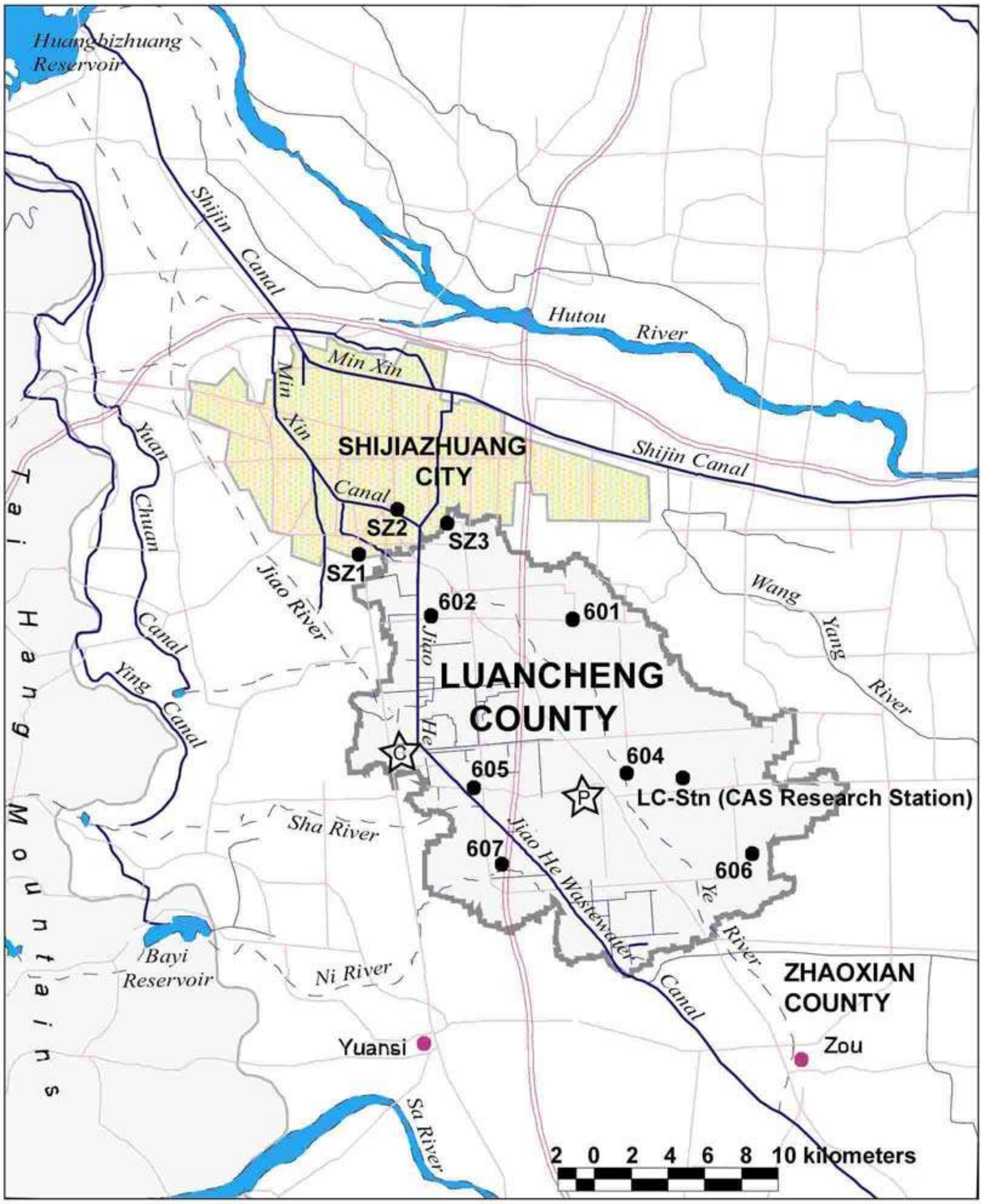
The climate is temperate, semi-humid monsoonal, with cold, dry winters and hot, humid summers. Sunlight is plentiful and temperatures are mild enough to grow ample temperate-climate crops (Zuo 1992). The lack of availability and the seasonal distribution of water are the factors most limiting agricultural production. The typical winter-wheat/summer-maize double cropping pattern requires 660 to 920 mm (1 mm = 10 m^3/ha) of water annually (Kendy et al. 2003b; Zuo 1992). Annual precipitation averages less than 500 mm in the north to 800 mm in the south, but varies unpredictably by more than 30 percent from year to year. Furthermore, the temporal distribution of rainfall does not correspond with crop needs. About 15-20 percent of the annual precipitation falls during the dry, windy spring planting season (March-May), leaving a water deficit for spring seedlings and maturing winter wheat (Zuo 1992).

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. Alluvial deposits consisting primarily of sand, reworked loess (silt), and clay extend to a depth of more than 500 m beneath the land surface in the center of the plain (Hebei Province Department of Geology and Mineralogy 1992). These deposits comprise the aquifers that supply groundwater to the North China Plain.

Luancheng County: Surrogate for the North China Plain?

The focus of this study is Luancheng County, Hebei Province, in the western part of the North China Plain (figures 1 and 3). Policy analysts note that water shortages tend to be localized, and identify upstream-downstream conflicts, urban-rural conflicts and excessive irrigation as the main perpetrators (Lohmar et al. 2003; Nickum 1998). Luancheng County provides a natural laboratory for assessing local impacts of each of these stimuli. The 397-km^2 rural county is downstream from three over-utilized rivers and adjacent to Shijiazhuang City, the highly industrialized provincial capital. A major agricultural producer, the county relies heavily on groundwater for irrigation. Because Luancheng County has been the subject of several detailed hydrologic and agricultural studies (Luancheng County Natural Resources Survey Team 1979; Luancheng County Water Policy and Integrated Water Resources Management Office 1993), a large historical database exists for quantifying hydrological change in response to long-term changes in agricultural policy.

FIGURE 3.
Location and features of Luancheng County and the surrounding area.



Note: Dots with numbers indicate locations of observation wells used to check groundwater balance calculations (Kendy et al. 2003c). Stars labeled “P” and “C” indicate locations of pharmaceutical- and chemical-producing industrial areas, respectively.

Sources: Chinese People’s Liberation Army Mapping Bureau 1970; Hebei Province Survey and Mapping Bureau 1999; Luancheng County Land Management Bureau 1996; Luancheng County Natural Resources Survey Investigation Team 1980; Ren and Wei 2000; Zhong and Guo 2000.

Luancheng County is located at latitude 38° north, at an elevation ranging between 45 and 70 m above mean sea level. Average monthly temperatures range from about -4° C in January to 25° C in July, with an average annual temperature of about 15°C and about 187 frost-free days annually. Most of the 461 mm of average annual rainfall occurs during the humid summer months, with very little during the spring and autumn, and even less during the cold, dry winters (Luancheng County Meteorological Bureau, unpublished data, 1971-2000). The Quaternary-age alluvial aquifer system underlying Luancheng County consists of laterally discontinuous layers 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). The county has long been a major producer of agricultural products, including wheat, maize, cotton, sorghum and millet. Rural industries manufacture chemical fertilizers, agricultural machinery, pharmaceuticals, paper, building materials, textiles and other commodities (Hebei Province Survey and Mapping Bureau 1999).

Luancheng County was selected for study primarily on the basis of data accessibility. Although in most respects Luancheng County is a reasonable surrogate for the North China Plain, its limitations in this regard should be identified before proceeding.

Luancheng County is located in the Hai River basin. Of the three basins that comprise the North China Plain, groundwater depletion could be considered most severe in the Hai River basin, which depends upon local precipitation for recharge. In contrast, the Huang and Huai basins extend considerably west of the North China Plain, and their larger watersheds contribute more surface water to the alluvial aquifers beneath the plain. In this regard, Luancheng County in the Hai River basin may represent a "worse-case" scenario compared to the Huai and Huang basins in the North China Plain.

Major hydrogeologic variations within the North China Plain relate to relative positions along natural flow paths. Generally, both groundwater and surface water flow eastward across the plain. Both deteriorate in quality and quantity along their flowpaths. Natural surface water is plentiful only along the westernmost fringes of the plain, where it is dammed and diverted, mostly into cities. Groundwater quantity also is greater in the west, due to more favorable geologic conditions—alluvium beneath the western part of the North China Plain is composed of coarser grained materials, such as sand and gravel, while the eastern part is dominated by silts and clays. Consequently, western aquifers are more permeable and yield larger quantities of water to wells than eastern aquifers. Luancheng County overlies a relatively permeable aquifer with some of the highest well yields in the region.

Due to their relative positions, the eastern parts of the North China Plain also have to contend with more salinity problems than their western counterparts. First, groundwater dissolves naturally-occurring minerals from the rocks and particles along its flowpath. These dissolved minerals build up in the water, rendering it progressively more saline as it flows eastward. Second, proximity to the ocean means that overpumping fresh groundwater induces seawater to flow into the aquifer to fill the voids. Finally, these flat, low-lying areas are difficult to drain, leading to soil salinization, which decreases crop yields and limits farming to salt-tolerant crops. In areas where shallow aquifers are saline, deep aquifers are used for groundwater extraction (Liu et al. 2001). Deep, "confined" aquifers are under greater pressure than shallow, "unconfined" aquifers, and therefore respond differently to pumping. Luancheng County, which is located in the western part of the North China Plain, has not encountered serious salinization problems and relies almost exclusively on shallow groundwater.

Table 1 compares Luancheng County to the North China Plain as a whole. Topographically and climatically the two are similar. Hydrogeologically too they appear similar because both rely upon the same alluvial aquifer system. However, Luancheng County is located near the western edge of the plain, and thus overlies relatively coarse-grained alluvium with generally fresher and more abundant groundwater than most of the North China Plain. These favorable conditions allow for intensive groundwater pumping in Luancheng County without the consequent salinity problems encountered more to the east. Thus, as table 1 indicates, grain yield and percentage of cultivated and irrigated land in Luancheng County exceed the regional average. Proximity to Shijiazhuang City explains the differences in water sources, and possibly also in population density, between Luancheng County and the rest of the North China Plain. Wastewater discharge from Shijiazhuang City is channeled into Jiao He wastewater canal (figure 3), which supplies irrigation water for the western part of Luancheng County.

TABLE 1.
Comparison of characteristics between Luancheng County and the North China Plain.

Characteristic	North China Plain	Luancheng County
Area (km^2)	320,000[a]	379[b]
Average annual temperature (°C)	10-16[c]	15[d]
Frost-free days per year	175-220[e]	187[d]
Altitude (m)	0 - >100	45-66[d]
Average slope (percentage)	1[e]	1[d]
Aquifer material	Alluvium	Alluvium
Principal crops	Wheat, maize, cotton[d]	Wheat, maize, cotton[b]
Grain yield (kg/ha)	About 5,000[f]	7,291[g]
Water source	Groundwater, surface water	Groundwater, municipal wastewater
Percentage of total cultivated land	50[e]	81[g]
Percentage of cultivated land under irrigation	56[e]	99[g]
Population	214,000,000[a]	361,279[g]
Population density (people/ km^2)	669	953

a. Liu et al. (2001)

b. Shijiazhuang Statistics Bureau (1949-2000), Luancheng County Chronicle Compilation Committee (1995). Land area also reported as 397 km^2 (Hebei Province Survey and Mapping Bureau 1999; Luancheng County Water Policy and Integrated Water Resources Management Office 1993.)

c. Huang (1988b)

d. Hebei Province Survey and Mapping Bureau (1999)

e. Yang (1991)

f. Based on Fuyang River basin data (Wang Jinxia, Center for Chinese Agricultural Policy, personal communication, 2000).

g. Shijiazhuang Statistics Bureau (1949-2000).

Hydrogeologic distinctions notwithstanding, Luancheng County serves in this study as a surrogate for the North China Plain. However, throughout the analysis, it is prudent to remember that we are considering the unique cultural and hydrologic conditions of a rural, western part of the plain, adjacent to and downstream from a large urban area.

Historical Overview

We begin with a brief history of the institutional changes that potentially affected water management in Luancheng County. Because of the county's rural character, we focus on agricultural policy. A complete history is obviously beyond the scope of this paper. Relevant aspects have been detailed by Huang (1998), Xu (1990), He (1991), Kang and Young (1998), McMillan et al. (1989), Stone (1988), Rozelle et al. (1997), Ash (1988), Chinese Hydraulic Engineering Society (1991), Taylor (1988) and many others. First, we summarize the most salient changes that define four distinct phases of water-resource development in the history of the People's Republic of China.

Chinese Agricultural Policy

The People's Republic of China was founded in 1949 with the Communist defeat of the Guomindang regime. From 1949 to 1958, the new nation was intently rebuilt after decades of war and chaos. Although it closely followed the Soviet model of urban industrial development, rural areas—the stalwart backbone of the Communist revolution, and home to the vast majority of the population—were not ignored. Large investments of both labor and capital fostered agricultural development. Numerous large-scale surface-water irrigation systems were constructed during this period.

Collective ownership of land and capital defined the commune system era from 1959 to 1978. The "iron rice bowl" guaranteed income, regardless of the level of effort invested. Consequently, farmers had little incentive to work hard or to manage collective resources efficiently. The government centralized planning and maintained tight control of production. Economic policy stressed adjustments, subsidies and crop quotas to guarantee supply, production, and allocation to urban industries and workers. To further fuel development, the government invested heavily in agricultural capital assets and technology. The rural labor force was readily mobilized for infrastructure construction and maintenance. However, insufficient training and motivation resulted in generally poor quality construction. During this period, the emphasis of water-resource development in North China shifted from surface water to groundwater, and irrigated areas throughout most of the country greatly increased in size and importance.

China's development path changed in 1976 after the death of Mao Zedong and the arrest of the "gang of four." Power shifted to Deng Xiaoping, who launched major reforms in 1978. By the early 1980s, the reforms had swept throughout the country. The commune system was abolished. Planning and control were decentralized. The new rural production responsibility system shifted primary accountability for field operations and income distribution from the collectives to individual households. Price, tax and quota systems were adjusted. A provision allowing households to keep or sell on the free market whatever they produced in excess of tax obligations instantly renewed personal incentive for production. Annual per capita rural real income increased nearly fourfold from 1978 to 1995 (Huang 1998a).

Impacts of the reforms were most pronounced during the early reform period from 1979 to 1984. Grain yields increased dramatically throughout China, at an average annual rate of 5.9 percent (Huang and Rozelle 1995). Rural economies diversified and specialized households emerged. As production efficiency increased, labor surpluses became evident. At the same time, government expenditure on agriculture decreased, the central government's financial support of local water management and environmental bureaus ceased, and the breakdown of the communal organization system led to a decay of water-management systems.

During the later reform period, from 1985 to 2000, the economy continued its transition from self-sufficiency to commodity-based after having absorbed the initial impacts of decollectivization. Rural economic policies extended market and price regulations by reforming the state-monopolized purchase and marketing system. Technical advances replaced personal incentive as the primary means for increasing grain yields, as China accelerated its transition from traditional to modern agriculture. As rural land tenure security improved and crop production quotas ended, production shifted to more diverse and profitable crops. New rural industries absorbed some of the surplus agricultural labor and raised rural incomes. The emphasis of water-resource development began to shift from supply to management, as the government implemented policies to control water use.

Although distinct in most respects, a common and critical thread weaves the four periods together: "Food self-sufficiency has been and will continue to be the central goal of China's agricultural policy" (Huang 1998a). A stable or increasing supply of water for irrigation has always been an implicit requirement for achieving this goal.

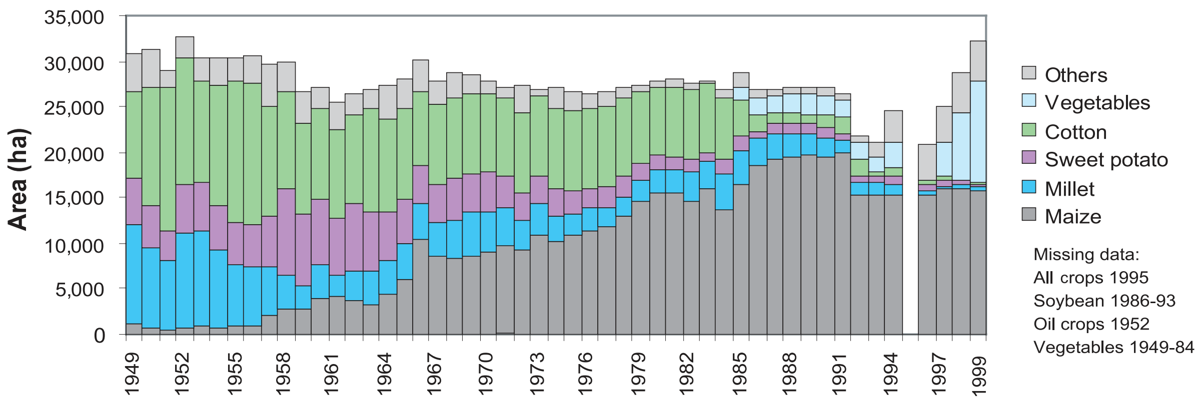
Water Management in Luancheng County

These agricultural policies, though presented here as a mere skeletal outline, profoundly influenced water management in Luancheng County. Although the county has always been a key agricultural producer, institutional developments over the last 50 years have fostered considerable changes in its agricultural systems, which are both an indicator of, and a mechanism for, changes in water management.

Pre-1949

Prior to irrigation development, and continuing into the early years of the People's Republic of China, rainfed cotton, millet, sorghum and sweet potato—all summer crops—were the primary products of Luancheng County (figure 4.1). Some winter wheat was also grown, requiring the hauling of water from shallow brick wells for irrigation (figure 4.2). At most, three grain crops could be produced every 2 years.

FIGURE 4.1.
Cropping history of Luancheng County, 1949-1999—summer crop sown areas.

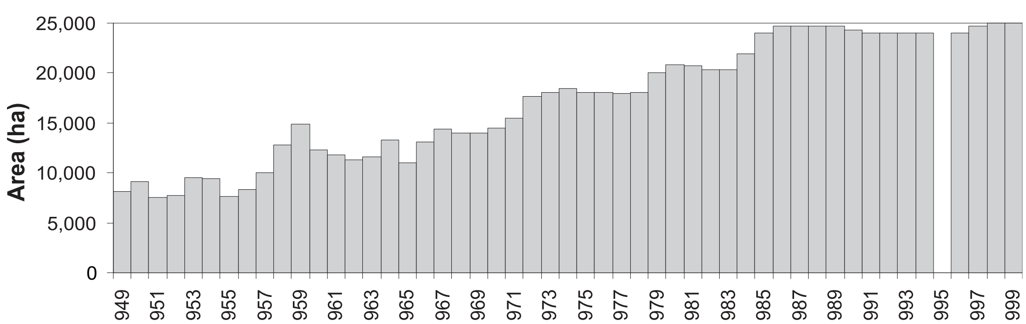


Note: "Other" summer crops include orchards, sorghum, oil crops and soybeans.

Source: Shijiazhuang Statistics Bureau (1949-2000).

Before major irrigation development, runoff from the Tai Hang Mountains flowed eastward into Luancheng County via the Jiao, Sha, and Ni rivers (figure 3). Seepage from the river channels replenished groundwater in underlying aquifers, and springs arose in Luancheng County. The irregularity of seasonal rains and the flatness of the landscape caused periodic flooding, begetting grave economic losses (Luancheng County Chronicle Compilation Committee 1995).

FIGURE 4.2.
Cropping history of Luancheng County, 1949-1999—winter wheat sown area.



Source: Shijiazhuang Statistics Bureau (1949-2000).

Nation Rebuilding, 1949-1958

Serious flood-control efforts began in 1950 with the channelization of the Jiao River (Luancheng County Chronicle Compilation Committee 1995), followed in 1958 by the damming and diversion of the Sha and Ni rivers (Zhang et al. 2000) along the eastern front of the Tai Hang Mountains (figure 3), where topographic and geologic conditions favor reservoir construction. By 1963, the Sha and Ni rivers no longer flowed into Luancheng County (Luancheng County Water Policy and Integrated Water Resources Management Office 1993). Surface water is now controlled to the extent that occasional releases from Huangbizhuang Reservoir into Shijin Canal (figure 3) constitute the only remaining streamflow into Shijiazhuang City (Lin and Yang 1991), and wastewater from Shijiazhuang City constitutes the only streamflow into Luancheng County. Jiao He wastewater canal, the straightened and concrete-lined relic of the old Jiao River, was built in the 1950s to convey municipal discharge away from the rapidly industrializing Shijiazhuang City. Farmers first began using the wastewater for irrigation in 1956 (Luancheng County Chronicle Compilation Committee 1995). However, due to lack of distribution systems, the wastewater-irrigated area was limited to the immediate vicinity of the main canal (Shijiazhuang City Bureau of Agriculture 1998). Thus, the irrigation-construction boom that swept the nation in the 1950s (Chinese Hydraulic Engineering Society 1991) actually left Luancheng County drier than before, as streams that had previously watered the county were diverted to other areas.

Commune Era, 1958-1978

It was groundwater irrigation that brought the first significant improvement to farming in Luancheng County. After a few false starts (760 wells were built in 1959, then abandoned within months due to faulty construction), government technical and financial infusions in the 1960s facilitated the rapid proliferation of drilled, mechanized wells (Luancheng County Chronicle Compilation Committee 1995). Groundwater irrigation immensely improved crop yields, enabling continuous cropping with two harvests every year (Dong 1991; Yang 1991). Although water-table declines were evident, Luancheng County was hailed as a "Model County" for increasing crop yields through groundwater irrigation (Luancheng County Chronicle Compilation Committee 1995). However, because farmers lacked personal incentive, irrigation was not always efficient (Ma Qijun, Deputy Director of Shijiazhuang Institute for Agricultural Modernization, Shijiazhuang, personal communication, 2001) and grain production remained low through the 1960s (Shijiazhuang Statistics Bureau 1949-1999).

Heavy government investment in agricultural technology in the late 1960s to the early 1970s set the stage for later changes in cropping patterns. During this period, both synthetic phosphorus fertilizers and high-yield hybrid wheat and maize varieties were introduced. Combined with free and open access to groundwater for irrigation, these technical advances led to increased grain yields through the 1970s (Shijiazhuang Statistics Bureau 1949-1999).

If technical advances were the only factors controlling cropping patterns in Luancheng County, production would have shifted almost immediately to the winter-wheat/summer-maize rotation observed today. But the shift was delayed by quotas for relatively low-yielding cotton and by a lack of incentive to produce in excess of the quotas. Due to their low labor and water requirements, sweet potatoes were the main subsistence crop during the commune era, and farmers grew other crops only to fulfill government quotas (Ma Qijun, Deputy Director of Shijiazhuang Institute for Agricultural Modernization, Shijiazhuang, personal communication, 2001).

Like all means of production in China, groundwater was managed collectively. Most wells drilled in Luancheng County in the 1960s and 1970s were large-capacity (100 m^3/hour), shallow wells less than 20 m deep (Li Suoyi, Director, Water Resources Division, Luancheng County Water Affairs Bureau, personal communication, 2001). Earth-lined ditches conveyed water from wells to fields. Water-transit losses were about 60 percent (Cao and Zhang 1994). Working collectively discouraged conservation of shared resources, including water and electricity (for pumping). In 1972, following several consecutive dry years (including 1969 when 80 percent of the more than 3,000 mechanized wells in the county ran dry), the government organized 114 drill rigs to construct 1,253 new wells (Luancheng County Chronicle Compilation Committee 1995). Water-table rises during several consecutive wet years in the late 1970s convinced scientists that exploitation was sustainable at the existing, or even increased rates (Luancheng County Natural Resources Survey Team 1979). Therefore, policies continued to encourage unregulated groundwater use as a means of increasing crop production. With drilling of wells, electrical power and water subsidized, brigade leaders ordered and enforced irrigation 24 hours per day (Zeng Jianghai, retired Director, Luancheng Agro-Ecological Research Station, personal communication, 2001).

Early Reform, 1979-1984

Production in Luancheng County was decollectivized from communes to households in 1979-1982. Because there was a market for excess produce, farmers' profits became linked to their labor inputs. With personal profits as motivation, grain production increased immediately. Since the reforms, crop yields in Luancheng County have nearly doubled (Shijiazhuang Statistics Bureau 1949-1999).

However, central government planners to a large extent still controlled the crop structure. Even after the reforms were instituted, cotton production persisted in Luancheng County, despite its much lower yields compared to irrigated, fertilized maize. Government cotton quotas effectively delayed the complete shift to maize until the early mid-1980s, when cotton was stricken by disease coinciding with a demand decline. At that point, farmers began to purchase cotton from elsewhere to fulfill their quotas (which ended in 1987), and replaced their cotton crops with maize (Yang Shufen, Zhang Cun Village Leader, Luancheng County, personal communication, 2001).

By then, regional water-table declines had become persistent (Zhu and Zheng 1983). Serious concerns led the Ministry of Water Resources and Electric Power to issue regulations in 1981 to strengthen groundwater management. But at the local level, government leaders remained focused on grain production. In 1984, the county again began offering subsidies for well construction (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001). This move not only enabled an expansion in wheat production, but also facilitated the shift from cotton to the less drought-resistant maize.

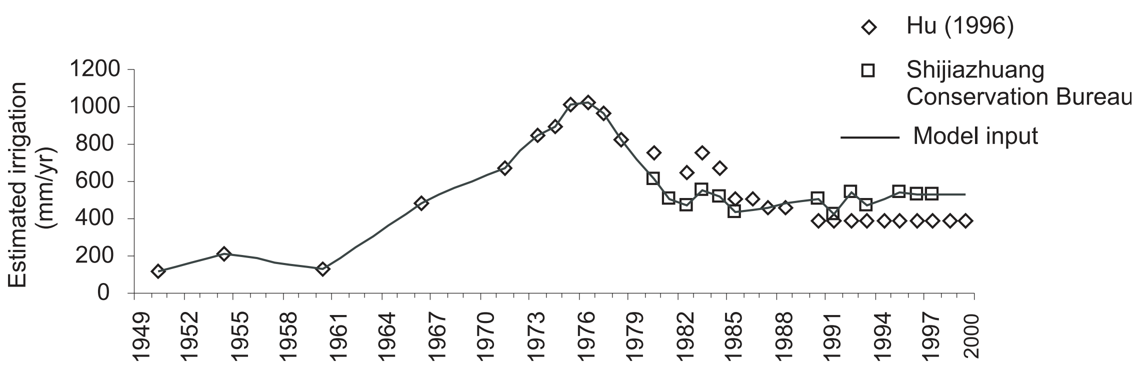
The transition from communal water management went smoothly in Luancheng County compared to areas served by large-scale irrigation systems, which suddenly lost their central organization during the reforms. Groundwater withdrawals, in contrast, were never centrally organized. Nevertheless, the coincidence of groundwater depletion with the economic reforms fundamentally changed water management in Luancheng County. In the early 1980s, water-table depths dropped beyond the reach of the large-capacity, communal wells, just as farming and irrigation management decentralized. Along the Jiao He wastewater canal, municipal wastewater replaced the now inaccessible groundwater. But in most of the county, as each shallow well was retired, several deeper (60-70 m), lower-capacity (40 m^3/hr), family-operated wells replaced it (Li Suoyi, Director, Water Resources Division, Luancheng County Water Affairs Bureau, personal communication, 2001). In this new economic milieu, household enterprises specializing in well-drilling emerged to compete with government drilling teams. Well ownership and management began to shift from villages to more efficient, quasi-private arrangements (Wang and Huang 2002). With the wells now located closer to the fields they irrigated, delivery efficiency improved and irrigation times were reduced to daylight hours only (Zeng Jianghai, retired Director, Luancheng Agro-Ecological Research Station, personal communication, 2001). Groundwater pumping for irrigation decreased from about 1,020 mm/year in 1976 to about 390 mm/year in 1996 (figure 4.3), with no losses in crop yield.

With profits now tied to labor, farming became more efficient and fewer workers were needed in the fields. But the rural population continued to grow. Tight restrictions on migration forbade self-sufficient rural residents from seeking coveted job opportunities in cities, where the government was obliged to provide food and housing subsidies. By 1985, the population of Luancheng County had grown to 292,500, out of which only 11,400 were employed in sectors other than agriculture (Shijiazhuang Statistics Bureau 1949-2000). Thus, the rural labor surplus emerged as a serious social concern.

Later Reform, 1985-2000

A proliferation of small-scale rural industries, or "township and village enterprises" (TVEs), joined the existing pharmaceutical, agro-chemical and agricultural-machinery factories in Luancheng

FIGURE 4.3.
Irrgation history of Luancheng County, 1949-1999—estimated pumping for irrigation.



Note: "Pumping" in the 1950s was primarily hauling, rather than pumping, from shallow, brick-lined wells. "Model input" indicates groundwater pumping and irrigation values used to calculate annual water balances (Kendy et al. 2003c; Kendy et al. 2003b).

Sources: Hu (1996); Hu, personal communication; Shijiazhuang Water Conversation Bureau (1949-1999).

County, providing employment for displaced farm workers, increasing local production and augmenting individual incomes. Economic output from Luancheng County increased by nearly one order of magnitude, from 350 million yuan in 1986 to 3.3 billion yuan in 1999 (Shijiazhuang Statistics Bureau 1949-2000). The population officially employed in the non-agricultural sector grew to 26,731 (Shijiazhuang Statistics Bureau 1949-1999).[1]

Off-farm income from the TVEs effectively changed local consumption and cropping patterns. With outside income, rural families could afford to purchase rice on the open market, replacing millet as their staple crop (Nie Zai Liang, farmer, Nie Jia Zhuang Village, Luancheng County, personal communication, 2001). By the late 1990s, millet production had almost completely ceased in Luancheng County. But rather than replacing millet with more maize, cash crops rapidly filled the void (figure 4.1). In the late 1990s, China achieved a grain surplus, which drove grain prices down. Meanwhile, demand grew for melon, vegetables, peanuts and turf to supply the increasingly affluent Shijiazhuang City. The area devoted to these relatively irrigation-intensive crops began to increase rapidly, and is likely to continue to do so, at least as long as grain prices remain low. Thus, the final lifting of grain quotas in 2000 had little effect on production, as other incentives had already influenced planting. Water-saving technologies such as green houses and drip and sprinkler irrigation are being phased in with many of the new cash crops (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001).

With the rise of TVEs, competition over water between local industry and agriculture intensified. However, groundwater withdrawals for county industries were still less than about one-tenth the withdrawals for irrigation (Shijiazhuang Water Conservation Bureau 1949-1999). More serious was the competition with Shijiazhuang City, which until 1997 depended solely on groundwater (Zhu Wenzhuang, Director, Industrial and Domestic Water Supply; Jia Bingshan, General Office Director; Yin Xianggong, Senior Hydrogeologist, Shijiazhuang Urban Construction Commission; and Liu Yonggang, Tap Water Company, personal communication, 2001). Groundwater-level declines were observed in Shijiazhuang City as early as 1964 (Shijiazhuang City Planning Bureau 1981), indicating that the city was extracting water, which, under natural conditions, would have flowed underground to Luancheng County. By the late 1990s, groundwater pumping for industrial and municipal use in Shijiazhuang (439 million m^3/year) was more than double the withdrawals for irrigation in Luancheng County (180-188 million m^3/year) (Shijiazhuang Water Conservation Bureau 1949-1999). To avert water shortages, county residents had no choice but to drill ever-deeper wells (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001).

This dilemma has not gone unnoticed by policymakers. But, while the central government issued strong environmental protection laws (Cannon and Jenkins 1990; Lou and Chen 1985; Qu 1991), no funds were made available to local agencies for their implementation and enforcement. Instead, financing reforms forced provincial and county-level water and environmental bureaus to turn to their water users for operating expenses (Ma and Ortolano 2000; Palmer 1998). Although, in principle,

[1] This figure is probably grossly underestimated. The real number of Chinese farmers is about one third the quantity officially reported as *nongmin*, defined for statistics purposes as people with countryside registrations, regardless of their employment status (Zhu 2001).

water fees are calculated on the basis of water-supply cost (Xu 1987), in practice, fees are limited by the ability of water users to pay. In 1988, a small water-resource fee was implemented for state-owned and city industries in Luancheng County, but no fee was implemented for farmers, who could not afford additional operating expenses.[2] However, farmers who drill new wells are obliged to obtain permits, through which the spacing between wells is regulated. The fee revenues are sufficient to fund the County Water Affairs Bureau, but not to finance water conservation countywide (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001).

Nevertheless, as a "National Demonstration County" for water saving, Luancheng County has benefited from a cost-sharing program in which the provincial, prefecture, and county governments and the farmer contribute 30, 30, 30, and 10 percent, respectively, to water-saving projects. As a result, in 2001, sprinklers watered about 2,900 ha, drip- and micro-irrigation watered about 20 ha, and underground PVC and concrete pipes delivered water to about 6,700 ha.

Water Use in Luancheng County

As water management evolved, water-use patterns changed accordingly. Chief among these changes was the rate at which groundwater was withdrawn from aquifers. Irrigation is the major user of groundwater in Luancheng County (Shijiazhuang Water Conservation Bureau 1949-1999) and indeed throughout the North China Plain (Nickum 1998; Xu 1990). Based on the cropping and water-management history, a continual increase in pumping from the 1960s might be expected, at least until the irrigation-dependent winter-wheat sown area peaked in 1986 (figure 4.2). The concurrent increase in winter wheat depends on irrigation water. The concurrent increase in maize-planted area (figure 4.1) also increased water demands because maize replaced more drought-resistant crops.

Considering the trend toward increased water demand, one might assume that groundwater pumping similarly increased over time. But the available pumping data and reliable independent estimates refute these expectations. Figure 4.3 shows annual groundwater pumping data for the 13 years that it was published by the Shijiazhuang Water Conservation Bureau, juxtaposed with estimates published by Professor Hu Chensheng, Director of the Chinese Academy of Sciences, Luancheng Agro-Ecological Research Station (Hu 1996).[3] Hu's estimates are based on a wide variety of reports and data sources, including Water Conservation Bureau figures, extrapolation from the metered discharges of selected wells and irrigation canals, calculations based on groundwater declines, and/or approximations based on the number of wells reported in the county (Hu Chenseng, personal communication, 2001). Hu indicates that pumping rates increased during the 1960s, when mechanized pumps first became widely available, then decreased significantly in the late 1970s to the early 1980s,

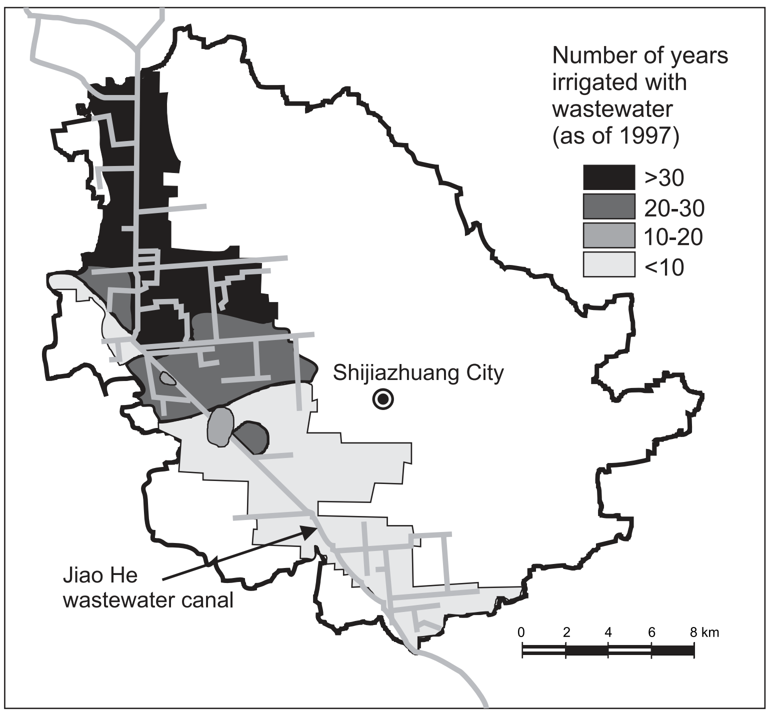
[2]Nickum (1998) maintains that farmers are fully capable of paying the full cost of water, and that "…the real problems with increasing water charges to agriculture tend to lie elsewhere, such as in the political unpalatibility of the idea."

[3]Professor Hu reported his figures in mm/year, whereas the Bureau reported its figures in m^3/year. To convert to comparable units, we divided the Bureau's numbers by "paddy field and irrigated land" (Shijiazhuang Statistics Bureau 1949-2000) and "groundwater irrigated area" (Shijiazhuang Water Conservation Bureau 1949-1999).

concurrent with economic reform. Both sources indicate relatively stable pumping rates after the mid-1980s.

Another important water-use trend is the increasing dependence on municipal wastewater for irrigation in the western one-third of Luancheng County. As Shijiazhuang City grew, it generated more and more wastewater, which discharges into Luancheng County via the Jiao He wastewater canal (figure 3). Meanwhile, the water table (or aquifer surface) beneath Luancheng County declined rapidly. Irrigators in most of the county had no choice but to replace dry wells with deeper ones. But irrigators along Jiao He canal instead switched their reliance from groundwater to the cheaper, more easily accessible, nutrient-rich wastewater. Thus, the area of wastewater-irrigated cropland has grown steadily[4] since its introduction in 1956 (figure 5).

FIGURE 5.
Locations of wastewater irrigated areas, Luancheng County, 1960s-1990s.



Source: Modified from Shijiazhuang City Bureau of Agriculture (1998).

[4] Consistent information regarding wastewater irrigation in Luancheng County is difficult to obtain. For further explanation, see annex 1.

Assessing Hydrologic Impacts

A quantitative analysis[5] of hydrologic changes affecting Luancheng County from 1949 to 2000 lends insight into causes and potential solutions to the steady groundwater declines. Although previous investigators calculated annual water balances for Luancheng County (Luancheng County Natural Resources Survey Team 1979; Luancheng County Water Policy and Integrated Water Resources Management Office 1993), none evaluated the long-term hydrologic changes needed to isolate the root cause of groundwater depletion.

A water balance is a simple accounting method to quantify hydrologic changes. All water-balance equations have the form:

$$\text{Inflows} - \text{Outflows} = \Delta S \qquad (1)$$

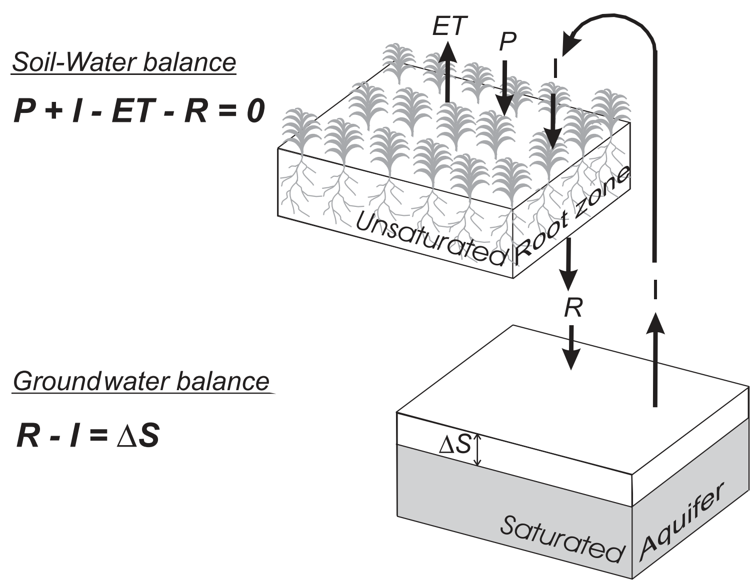
where DS is the change in water stored in the system. All terms are expressed as volume/time.

To assess hydrologic changes in Luancheng County, we begin by examining the annual water balance of the crop root zone, or approximately the top 2 m of the soil profile. A simple soil-water balance equation for the root zone of irrigated cropland (figure 6) is:

$$P + I - (ET + R) = \Delta S, \qquad \Delta S = 0 \qquad (2)$$

where *P* is precipitation; *I* is irrigation water applied to crops; *ET* is crop evapotranspiration; *R* is drainage from the soil profile; and ΔS soil-moisture change, which is usually negligible over a one-year time span.

FIGURE 6.
Generalized soil-water and groundwater balances of Luancheng County.



Note: P is precipitation; *I* is irrigation water pumped from the aquifer and applied to crops; *ET* is crop evapotranspiration; *R* is drainage from the soil profile, which recharges the aquifer; ΔS is change in groundwater storage, as evidenced by water-table declines.

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[5]For details, see annex 2.

Now, consider values for these variables in Luancheng County. Average annual rainfall (P) is about 460 mm/year (Luancheng County Meteorological Bureau, unpublished data, 1971-2000). Applied irrigation has varied significantly over time (figure 4.3), so I will remain in variable form. The average crop assemblage in Luancheng County from 1971-2000 (figures 4.1 and 4.2) evapotranspired (ET) about 660 mm/year (Kendy et al. 2003b). Rearranging the soil-water balance (equation 2), we find that $R = P + I - ET = I - 200$. That is, the amount of excess water that drains from the soil profile is always about 200 mm/year less than the amount applied as irrigation, regardless of the quantity applied.

Next, we move to a simple groundwater balance,[6] shown schematically in figure 6. Ignoring for now all lateral inflows and outflows, a simple groundwater balance can be expressed as:

$$R - I = \Delta S \qquad (3)$$

where R and I are defined the same as for the soil-water balance and ΔS is the change in groundwater volume stored in the aquifer.

Now we note that R represents not only drainage from the soil profile, but also recharge to the underlying aquifer, and that I is not only irrigation water applied to crops, but also the same quantity of irrigation water pumped from the aquifer. This is a realistic model for most of Luancheng County, which has no other source of irrigation water.

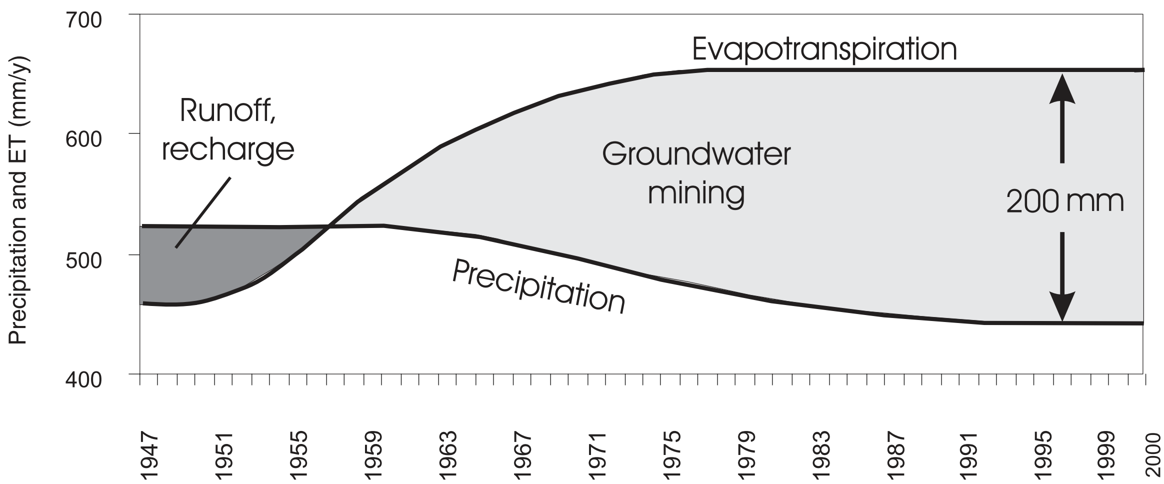
Solving equation 3 for ΔS, we find that $\Delta S = (I - 200) - I = 200$ mm/year. This result is significant because it shows that, regardless of the quantity of water pumped from the aquifer, groundwater storage decreases by 200 mm/year. Assuming the specific yield of the aquifer is 0.2 (Lin and Yang 1991), this equates to an annual water-table decline of 1 m/year.[7]

Figure 7 shows schematically how the water balance has changed over time, as the irrigated area has grown. Only precipitation and evapotranspiration are shown because they compose the only actual inflows and outflows from the hydrologic system depicted in figure 6; recharge and irrigation are internal flows. Average annual precipitation has decreased in Luancheng County, from about 540 mm/year in 1955-1980 to about 460 mm/year in 1971-2000 (Luancheng County Meteorological Bureau, unpublished data; data for 1955-1970 are for Shijiazhuang City). Many people blame groundwater declines for this decrease, so we account for it in figure 7. Evapotranspiration, meanwhile, has greatly increased, from about 460 mm/year when all crops were rainfed to an average of 66 mm/year in 1970-2000, under the cropping patterns shown in figures 4.1 and 4.2 (Kendy et al. 2003b).

[6] A zone of unsaturated geologic material containing no plant roots is inferred between the top and bottom block diagrams. The thickness of the unsaturated zone has increased over time as the water table, which demarcates the surface of the saturated zone, has declined. Water flows vertically through the unsaturated zone, from the soil profile to the aquifer.

[7] Dimensionless specific yield (S_y) may be thought of as the aquifer porosity. If $S_y = 0.2$, or 20 percent, then 20 percent of any aquifer volume contains water, and the other 80 percent contains geologic material (in this case, gravel, sand, silt and clay). Thus, for every 200 mm of water removed, the water table actually declines 0.2 m/0.2 = 1.0 m.

FIGURE 7.
General relationship between precipitation and evapotranspiration for cropland in Luancheng County, 1947-2000.

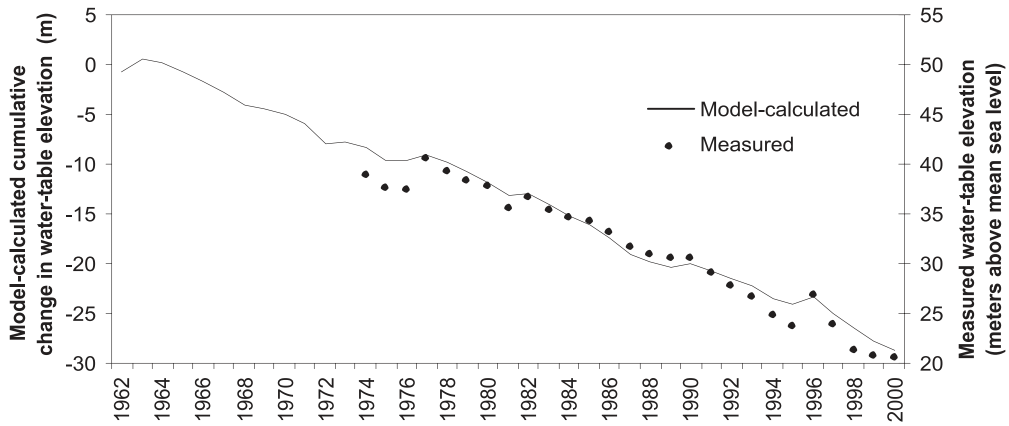


According to figure 7, before irrigation development and during the early years of small-scale irrigation, precipitation exceeded evapotranspiration. The excess water recharged the underlying aquifer and at times even filled the aquifer to capacity, resulting in runoff, as evidenced by the formerly springfed Ye river, which is now dry (figure 3). Later, as the irrigated area grew and winter wheat crops 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 came from groundwater mining, and the quantity mined is the difference between precipitation and evapotranspiration, or about 200 mm/year under the current cropping pattern.

This again explains why the rate of groundwater decline has been nearly constant (figure 2), despite significant decreases in pumping (figure 4.3). So long as both summer and winter crops are grown and all crop-water requirements are met, groundwater mining amounts to about 200 mm/year, regardless of the quantity pumped. The crops cannot use any groundwater withdrawals in excess of 200 mm/year. Instead, this excess irrigation water drains through the soil profile, eventually recharging the aquifer, and is therefore retained in the hydrologic system. By considering the entire hydrologic system, including both the soil profile and the underlying aquifer, we see that evapotranspiration is the only water actually depleted from the system.

Of course, precipitation and evapotranspiration vary from year to year more than what is shown schematically in figure 7. Therefore, to check this interpretation, Kendy et al. (2003b) calculated annual water-table declines for the 1949-2000 period based on the simple model shown in figure 6, while accounting for daily variation in crop-growth stage and climate. The cropping and irrigation history were simulated according to figures 4.1,4.2 and 4.3. The result, shown in figure 8, is that water-table declines calculated in this way agree closely with those actually measured in Luancheng County. Although this simple model ignores lateral groundwater flow, it seems to explain the historical groundwater depletion well.

FIGURE 8.
Water-table change due to agricultural water use in Luancheng County, 1962-2000.



Note: Model-calculated annual water-level changes (line) were calculated by subtracting pumping for irrigation (figure 4.3) from model-calculated recharge. Measured water-table elevations (dots) represent average December water levels observed beneath Luancheng Agro-Ecological Research Station (Chinese Academy of Sciences), indicated as LC-Stn in figure 3.

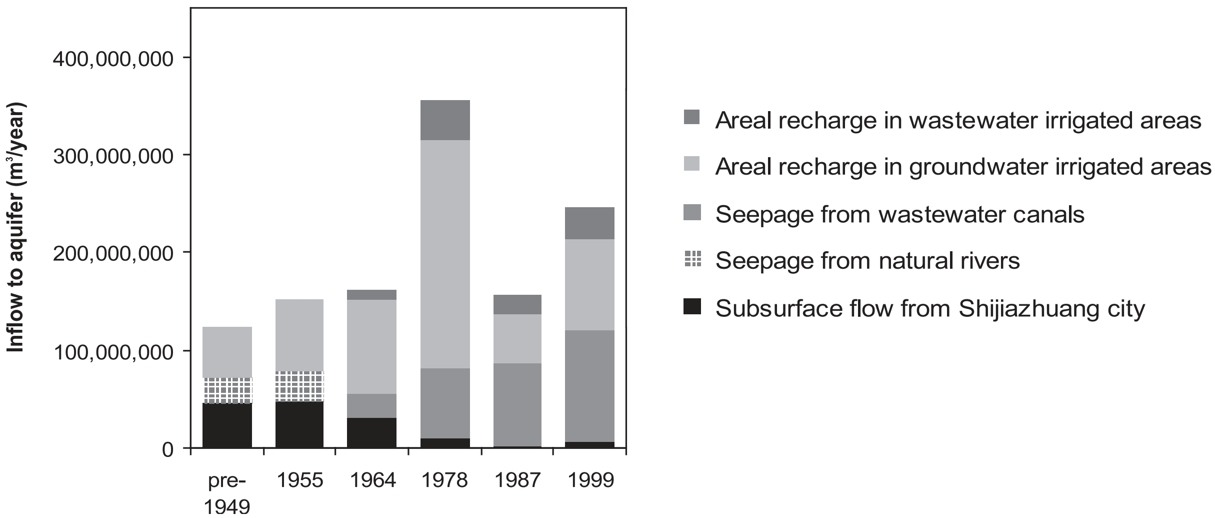
Nevertheless, without a full accounting of all flow components, the model is incomplete. Therefore, Kendy et al. (2003c) calculated complete, annual groundwater balances of Luancheng County under pre-development conditions and for the 1949-2000 period, accounting for the effects of stream diversion, urbanization, irrigation and climate changes. Also, rather than assuming that drainage through the soil profile is a constant fraction of precipitation and irrigation, as others have done, Kendy et al. (2003c) determined recharge independently, using a soil-water balance method based on crop, soil, and climate data (Kendy et al. 2003a). Other inflows and outflows were based on historical data and estimates.

The results are shown in figures 9.1 and 9.2, which graphically depict how the groundwater balance of the entire county has changed over time. Each important hydrologic change is shown: the cessation of inflow from natural streams, concurrent with the initial decline in outflow to springs and evapotranspiration from the water table, and the onset of groundwater pumping, foretelling the cessation of outflow to springs and evapotranspiration; groundwater flow reversal along the boundary with Shijiazhuang City; and increasing inflows of urban wastewater.

The important result is that, except for crop evapotranspiration, every other historic water-balance change was compensated for by another, consequent change. Stream diversions in the 1950s deprived Luancheng County aquifers of significant inflow, but the resulting water-table decline stopped a nearly equal outflow to springs and evapotranspiration from the previously high water table. Thus, the diversions essentially eliminated the flood hazard associated with a high water table without precipitating long-term water-table declines. Likewise, municipal pumping in Shijiazhuang City deprived Luancheng County of important subsurface recharge, but municipal wastewater discharge compensated for the loss. In contrast, due to crop evapotranspiration losses, seepage from irrigated cropland cannot fully compensate for groundwater withdrawals for irrigation. Thus, the previous conclusion remains valid: evapotranspiration constitutes the only water actually depleted from the hydrologic system.

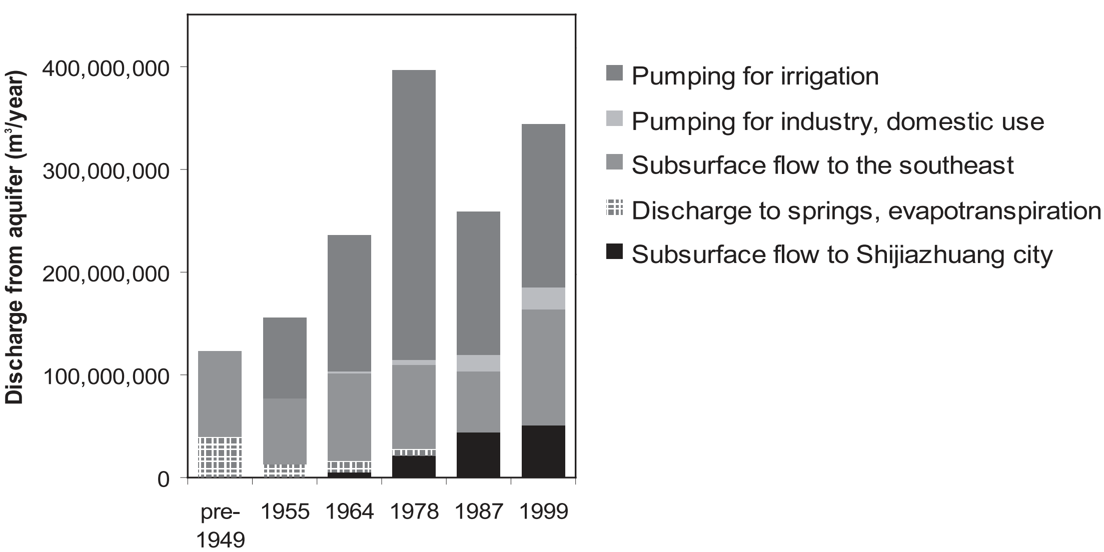
The only means to reduce the rate of groundwater declines beneath irrigated cropland in Luancheng County is to reduce crop evapotranspiration.

FIGURE 9.1.
Model-calculated annual groundwater balances of Luancheng County for selected years—inflows.



Note: Areal recharge consists of infiltrated precipitation and irrigation return flow.

FIGURE 9.2.
Model-calculated annual groundwater balances of Luancheng County for selected years—outflows.



Note: Areal recharge consists of infiltrated precipitation and irrigation return flow.

Balancing the Water Budget: Options for a Sustainable Future

Although conceptually the water-balance equation 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 including both the root zone and the underlying aquifer in our water-balance analysis, we can see that groundwater depletion is as regional as groundwater-irrigated cropland—the major land use on the North China Plain (Xu 1990)—and that the water resource is, indeed, "vanishing" into the air through evapotranspiration. Therefore, arresting the declining water table will entail more than local institutional changes. Groundwater declines will slow only when water depletion decreases, and will reverse only when net inflows exceed depletion. Theoretically, this goal may be achieved either by increasing inflows or by decreasing outflows.

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 what is needed to meet the regional deficit between precipitation and evapotranspiration. Moreover, water deliveries will be targeted primarily to cities and 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 not a solution for regional groundwater declines. Therefore, this section focuses on demand management. Unlike supply management, which targets specific receiving areas, these demand-management options have the potential to alleviate regional water shortages stemming from agricultural water use throughout the North China Plain.

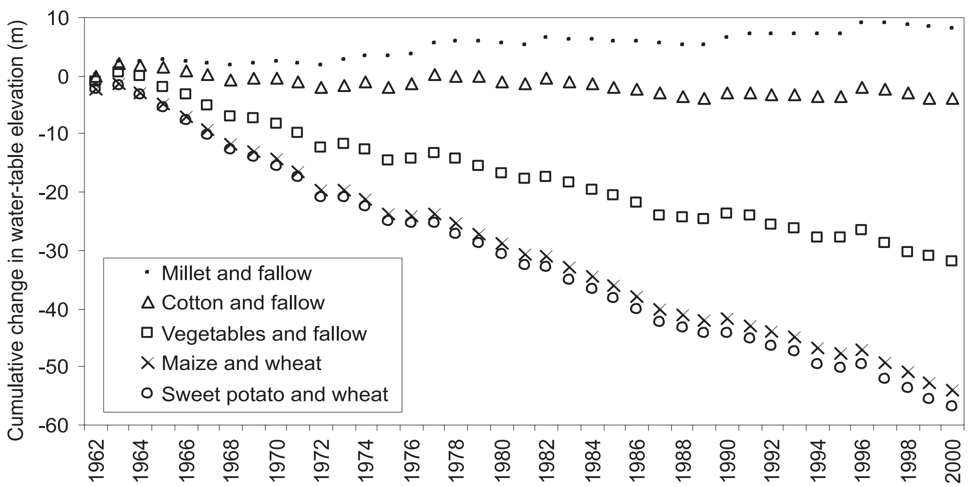
Crop Changes

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 and Rozelle 1999), replacing summer maize with spring maize every other year (Yu 1995), increasing maize production while decreasing wheat production and stopping wheat production altogether (Yang and 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 (figure 4.1).

Kendy et al. (2003b) 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 10) indicate that, regardless of which summer crop is grown, irrigated agriculture is not sustainable if winter wheat is

FIGURE 10.
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.



Source: Kendy et al. 2003b.

also grown. The impact of substituting maize with sweet potato is minimal, since most groundwater depletion results from winter wheat irrigation. 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 secondarily on the root depth and leaf area (Kendy et al. 2003a; Kendy et al. 2003b). Figure 10 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. However, simply substituting vegetable crops for wheat/maize may not generate sufficient water savings, due to the extended growing season of vegetables compared to summer crops.

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 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 (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001). However, 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 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 these "water-saving" techniques are introduced, because while these techniques reduce pumping, they simultaneously decrease irrigation return flow, or groundwater recharge. 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.

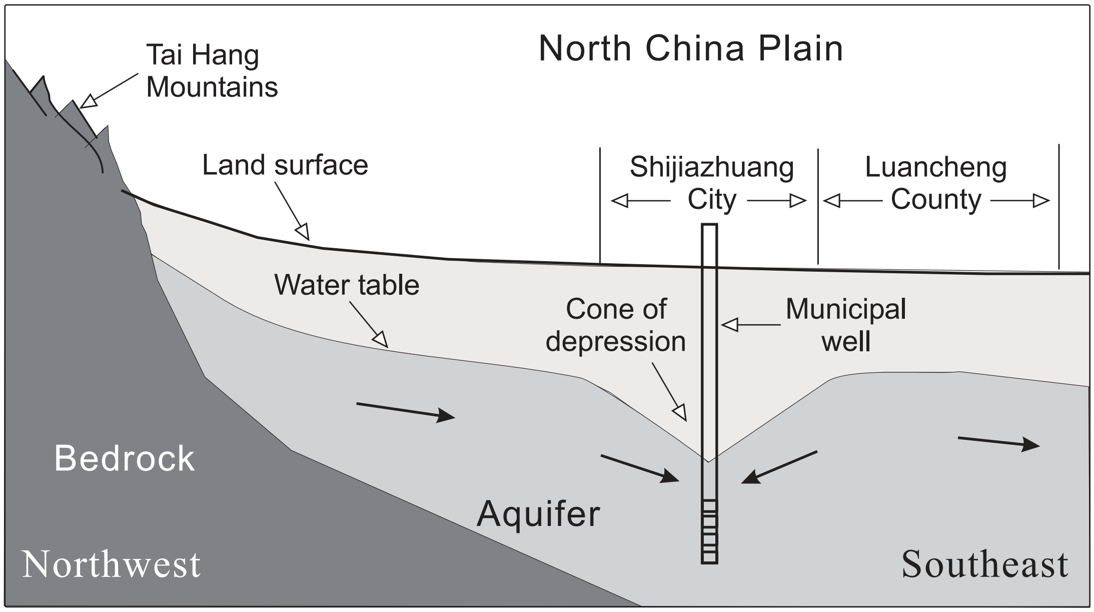
On the other hand, technologies that reduce the evaporation component of evapotranspiration do reduce outflow from the overall hydrologic system, and therefore can save water. However, the scope for reducing evaporation is relatively small because the crop cover is dense and the time period between crops is typically quite short. For example, mulching winter-wheat and summer-maize with plastic membranes or straw has been shown to reduce evaporation by 100 (You and Wang 1996) to 135 mm/year (Zhang Yongqiang, Shijiazuang Institute of Agricultural Modernization, personal communication, 2001) in the North China Plain without decreasing productivity. Greenhouses also can potentially save water because their artificially humid, windless environment reduces evaporation (L.D. Albright, Professor, Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY, written communication, 2002).

Urbanization

To employ a growing rural labor surplus and to narrow the income disparity between urban and rural residents, the Chinese central government recently began advocating rapid urbanization and industrialization of rural North China (Fu 2001; Gao 2001). With its focus on maintaining economic growth, the World Bank (2001) has also proposed a "water sector strategy" recommending urbanization. Foremost is its advice to divert even more of the rural water supply to fulfill the needs of the expanding urban industrial sector, where its marginal value is higher. With farming declining, the World Bank (2001) envisions a North China Plain population that is 52-63 percent urban by 2050—up from 21 percent in 1993—with only 10-15 percent of the population engaged in farming. 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 agricultural land to urban land use.

Proximity to large urban areas markedly influences local hydrology. Urban land surfaces tend to be impermeable. Therefore, precipitation

FIGURE 11.
Schematic cross section of the study area, illustrating hydrogeologic impacts of concentrated municipal well pumping.



Note: Solid arrows indicate dominant groundwater flow direction. Diagram is not to scale.

runs off, rather than recharging the aquifer immediately underlying the city. Overpumping 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 many cases extends laterally far beyond the city limits (Liu et al. 2001). Thus, 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 (figure 11). Additional impacts result from urban runoff and wastewater, which discharge onto adjacent farmland, where they may be used for irrigation.

Luancheng County is located immediately adjacent to and downstream from Shijiazhuang City (population 1.48 million), the heavily industrialized capital of Hebei Province (Xinhuanet.com 2002). Under natural, predevelopment conditions, groundwater flowed southeastward into Luancheng County from beneath Shijiazhuang City. Today, Shijiazhuang City's pumping wells extract about 439 million m^3/year (Liu et al. 2001) from its aquifer, which it shares with Luancheng County. As a result, the elevation of the center of the Shijiazhuang City cone of depression is less than 30 m above sea level, compared to more than 40 m at Luancheng County's well number 602 shown in figure 3 (Hebei Water Resources Bureau, unpublished data). The southeast-to-northwest water-table slope between the two effectively reverses the natural groundwater flow direction, enabling Shijiazhuang City to capture water for its wells which, under natural conditions, would have flowed into Luancheng County aquifers (figure 11). Instead, about 120-140 million m^3/year (Zhang et al 2000) of untreated municipal (domestic) and industrial wastewater from

Shijiazhuang City discharges into Luancheng County via the Jiao He wastewater canal.[8] This wastewater has surpassed natural stream seepage, lateral subsurface flow and precipitation as the primary source of recharge to aquifers in Luancheng County (Kendy et al. 2003c).

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. In many industrial uses, only a small fraction delivered to the industry is actually evaporated, but at discharges can be highly polluted.[9]

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 are around 1 yuan/m^3 (Nyberg and 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, and thus can reduce the size of the cone of depression. Already, Shijiazhuang has depleted two-thirds of its 60 m aquifer depth (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 (Brown and Halweil 1998; He 1991; World Bank 2001; Zhang and Zhang 1995). An exception is Tianjin (figure 1), which increased its industrial water recycling rate from 40 percent in the 1980s to 74 percent 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 and Imura 2001). Shijiazhuang City is currently attempting to implement its own industrial water-conservation measures. For every 10 million m^3/year not pumped, the average rate of groundwater decline beneath Shijiazhuang City could potentially decrease about 200 mm/year (assuming a specific yield[7] of 0.2 and a 250 km^2 cone of depression). With an industrial pumping rate of 340 million m^3/year (Shijiazhuang Water Conservation Bureau 1949-1999), Shijiazhuang City can significantly reduce the size of its cone of depression by following Tianjin's lead.

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[8]The quantity of seepage from the wastewater canal is difficult to ascertain. The Luancheng County Natural Resources Survey Team (1979) reported that in 1978, 120-140 million m^3/year of wastewater flowed into the county. Based on the types and areas of crops irrigated with wastewater, the team determined that 30-40 percent of this inflowing wastewater was used for irrigation. The rest evaporated, flowed south-eastward into Zhao County, and seeped from the canal into underlying aquifers. According to Luancheng County Water Policy and Integrated Water Resources Management Office (1993), estimated seepage from the canal was about 20 million m^3/year in the 1980s. The basis for this estimate was not given. In 1997, Shijiazhuang used 439 million m^3/year (Liu et al. 2001); presumably, most of this water eventually discharged to the wastewater canal. In addition, the canal conveys storm-water runoff from a 113 km^2 area of Shijiazhuang City. For further details, see annex 1.

[9]Depleted fractions in industries are often low when there is little enforcement of pollution regulations, or when the cost of water delivery is much less than the cost of recycling, reusing and cleaning water. But, return flows from industries are highly polluted relative to deliveries to industries (Molden 1992).

The scope for reducing municipal (domestic) water use may be more limited than for industrial water use. The 99 million m^3/year Shijiazhuang City pumps for domestic use[10] 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 per 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 and Imura 2001).

By treating and reusing urban wastewater, 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 lawns) could reduce delivery requirements. Water-depleting industries can be moved off the North China Plain. Shijiazhuang City's water-consuming industries produce pharmaceuticals, fertilizers, and other chemicals; and mill flour, brew beer and dye textiles. In addition, groundwater for central heating is piped through the city. Tianjin and Beijing have successfully altered their industrial structures to consume less water by encouraging water-thrifty 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 and Imura 2001).

Persistence of the cone depression beneath Shijiazhuang depends on management of wastewater flows. Only by increasing recharge to equal discharge can water-table declines be arrested. 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 and Resources 1994). For aesthetic purposes, Shijiazhuang City recently constructed Min Xin canal (figure 3), which is actually a ring-shaped, concrete-lined lake. The "canal" is filled with high-quality water from the Huangbizhuang reservoir, and the strips of land bordering it are being developed as parks. In principle, the "canal" leaks no water into the underlying aquifer and during large rainfall events, it discharges to Jiao He wastewater canal. If the "canal" lining were removed, Min Xin could become a receptacle—and infiltration basin—for treated wastewater. If 100 million m^3/year of wastewater were treated and artificially recharged, water levels beneath Shijiazhuang City could potentially could rise 2 m/year (assuming a specific yield of 0.2 and a 250 km^2 recharge area).

Runoff from the impermeable roofs and paved roads in urban areas can also 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 received through precipitation under pre-development conditions—probably more, because before urbanization, vegetation

[10]In 1997, Shijiazhuang City's wells pumped 439 million m^3/year (Liu et al. 2001), of which industry used 340 million m^3/year (Shijiazhuang Water Conservation Bureau 1949-1999), leaving 99 million m^3/year for domestic use.

consumed more water (Seaburn and 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/year.

From a hydrologic standpoint then, is urban land-use management a viable alternative to changing practices in irrigated cropland? Increasing urban water-use efficiency or treating water will improve water quality, change the groundwater flow paths, and reduce the depth of cones of depression. Ultimately, the average groundwater decline will depend on how much water is evaporated. The relative merits of urban versus agricultural land use, in terms of regional water-table declines, depend on the quantity of water each depletes from the hydrologic system. The current cropping pattern in Luancheng County evapotranspires an average of about 660 mm/year (Kendy et al. 2003b). Unfortunately, data are not available to determine the quantity of water that Shijiazhuang City depletes. However, it is commonly accepted that urban land use depletes much less water than crop evapotranspiration (Peter H. Gleick, Director, Pacific Institute for Studies in Development, Environment, and Security, Oakland, CA, personal communication, 2002). This assumption is reasonable because in agriculture the entire cropped land surface is covered with evapotranspiring plants, whereas the urban land surface is not. Replacing agricultural landscapes with urban landscapes could reduce regional groundwater decline, but may present significant socio-political challenges.

Water Pricing

Water has long been subsidized in China (Xu 1987), depressing water prices far below those of other countries. To encourage water conservation, many people advocate raising the price of water to better reflect its actual cost (Anderson and Leal 2001; Lampton 1983; Nyberg and Rozelle 1999; Zhang and Zhang 1995). However, it is not clear that such a policy change would necessarily benefit 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 and Rozelle 1999). 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 targets for water price increases than irrigators because of the advantages of industrial water-use efficiency discussed above. Moreover, with their much larger profit margins than farmers, industrialists have a better ability to pay, improving chances of successful implementation. 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/day (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001).

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

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. 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). 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. In the previous section, we presented some viable approaches for reducing evapotranspiration. Now, we examine options for combining these approaches to balance the water budget in the future at a landscape scale.

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 660 to 460 mm/year. Table 2 lists various land uses discussed above, 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. (2003b). For total fallow, estimated depletion is negligible, which assumes all weeds are eliminated and almost all rainfall infiltrates, as practiced in alternate years in the semiarid Great Plains of Canada and the United States. For urban land use, the actual depletion rate is not known. If we assume all wastewater gets treated, urban water depletion would be considerably less than depletion from irrigated

TABLE 2.
Estimated annual water depletion rates associated with various land uses .

Land use	Deple-tion (mm/year)	Notes and references
Cropland		
Winter fallow/summer millet	430	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	490	
Winter fallow/spring-fall vegetables	620	
Winter wheat/summer maize	730	
Winter wheat/summer sweet potato	740	
Mulched winter wheat/summer maize	630	Same as above. Water savings from You and Wang 1996.
Total fallow (rainfall harvesting)	0	Weed-free.
Urban	330	Assumes urban water depletion is half that of average Luancheng County cropland, 1971-2000.

land, so we arbitrarily assigned an urban depletion rate of 330 mm/year, or one-half the average evapotranspiration rate from cropland in Luancheng County (Kendy et al. 2003b).

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.

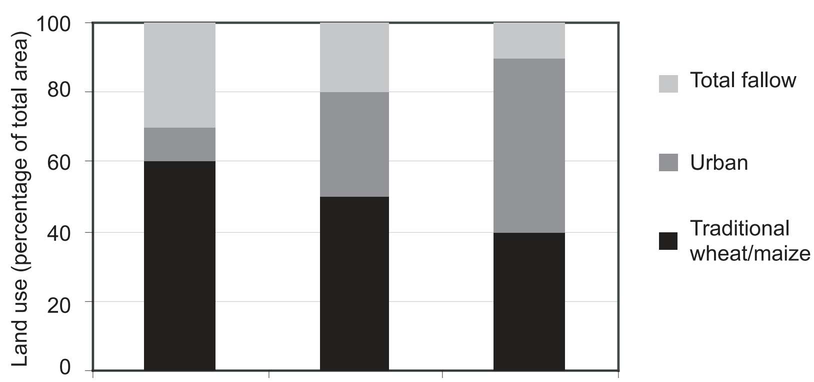
An infinite number of land-use combinations exist which, combined, deplete only 460 mm/year. Figures 12.1 and 12.2 illustrate several possibilities, based on the depletion rates listed in table 2. Each figure shows three possible combinations of winter wheat/maize crop rotation, urban land use and total fallow. Each stacked bar shows a different combination of these land uses which, combined, deplete only 460 mm/year.

Figure 12.1 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 12.1 may not gain acceptance in the North China Plain, where unused land is considered wasteful.

Figure 12.2 perhaps gives more politically palatable options. Instead of assuming traditional farming methods, figure 12.2 assumes that all wheat and maize are either mulched or replaced with vegetables. Either scenario would reduce crop evapotranspiration by 100-110 mm/year (table 2). As a result, more land can be urbanized and less land needs to be fallowed for a given percentage of cropland.

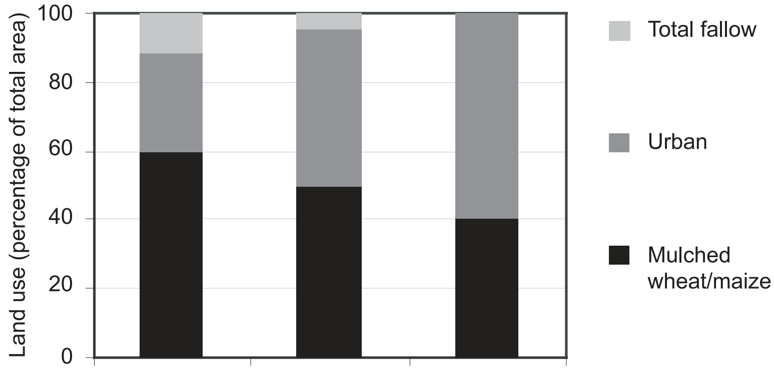
The third stacked bar on figures 12.1 and 12.2 represents 60 percent urban land use. If overall crop evapotranspiration were reduced by at least 100 mm/year and urban water depletion was 330 mm/year or less, then the bottom graph suggests that Luancheng County could stabilize

FIGURE 12.1.
Examples of land-uses which, combined, deplete approximately 460 mm/year of water—under the assumption that traditional flood irrigated winter-wheat/summer-maize rotation is maintained.



Note: Each stacked bar represents a different combination of land use: total fallow, urban and irrigated agriculture. Estimated depletion rates for each land use are listed in table 2.

FIGURE 12.2.
Examples of land-uses which, combined, deplete approximately 460 mm/year of water—under the assumption that all wheat and maize is either mulched or replaced with vegetable crops, thereby reducing evapotranspiration by 100 mm/year.



Note: Each stacked bar represents a different combination of land use: total fallow, urban and irrigated agriculture. Estimated depletion rates for each land use are listed in table 2.

the water table under this scenario without fallowing any farmland.

It should be noted that this assessment does not account for future changes in lateral flows across county boundaries. In reality, groundwater depletion in Luancheng County depends not only on local water management, but also on water-use changes in adjacent areas. Likewise, groundwater recharge due to periodic flooding was not factored into the analysis.

In addition to future land-use ratios, the physical layout of those land uses is also 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. Finally, access to wastewater is an important consideration in deciding which rural areas will remain irrigation-dependent, which might revert to rainfed agriculture and which will convert to potentially more productive industrial water uses.

Although the numbers used to construct figures 12.1 and 12.2—especially urban water depletion—are imprecise, the approach provides 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.

The 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 finding counters the long-standing, successfully implemented 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 inevitable. 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 and Zehnder 2001). A major challenge then, will be to introduce socially, politically, and economically acceptable incentives to reduce the irrigated area.

Conclusions

A vastly changing political and economic landscape over the past 50 years has led to major water-management changes in the North China Plain. However, a comprehensive water-balance analysis of Luancheng County, Hebei Province, indicates that a single, longstanding policy is responsible for steady groundwater declines. That policy is the promotion of groundwater pumping to meet the crop-water requirements not supplied by precipitation.

Attempts to make water use sustainable have centered on improving irrigation efficiency to reduce groundwater pumping. Indeed, pumping rates for irrigation in Luancheng County have decreased more than 50 percent since the 1970s. However, water-table declines have continued unabated. This is because the only significant inflows and outflows to and from this hydrologic system are precipitation and crop evapotranspiration, respectively. As long as the irrigated area remains unchanged, crop evapotranspiration remains constant. In Luancheng County, irrigated areas overlie the shallow aquifer, so any excess irrigation water supplied by groundwater pumping passes through the soil profile and replenishes the water supply. Thus, decreased pumping causes a corresponding decrease in groundwater recharge from excess irrigation, while precipitation and crop evapotranspiration remain unchanged. In this physical configuration, irrigation efficiency improvements save no water.

By considering the entire hydrologic system, including both the soil profile and the underlying aquifer, we found 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. Because urban areas deplete less water per unit land area with existing practices, increased urbanization will decrease rates of regional groundwater decline. But problems of pollution, already significant, will be of much greater concern than groundwater quantity unless wastewater treatment and reuse become central components of an integrated water-use strategy.

With far-sighted, regional planning, the limited water resources can be used sustainably to generate maximum social benefits. Success hinges on a realistic understanding of both local and regional water balances, and the hydrologic impacts of past and future policies. To reverse the trend of declining water levels, urban and rural water must be managed comprehensively, with net depletion rates no greater than natural replenishment rates.

ANNEX 1

Some Notes Regarding Water-Use Data

As Nickum (1995), Tuan (1998), and many others have lamented, Chinese land and water data present numerous challenges to researchers. This annex describes some of the challenges encountered during this project, and how they were addressed.

While both Hu (1996) and the Shijiazhuang Water Conservation Bureau (1949-1999) cite a decrease in groundwater pumping after the mid-1970s, their explanations differ. Hu and other local scientists attribute the pumping decrease to a reduction in the number of irrigation applications (Hu Chunsheng, Director, Luancheng Agro-Ecological Research Station, personal communication, 2001). In contrast, Water Conservation Bureau officials think the number of applications probably remained steady, but the quantity applied each time decreased due to water-saving technologies such as concrete pipes (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001). Other analysts attribute the decrease to an increase in delivery efficiency associated with the transition from communally-managed, large-capacity to quasi-privately-managed, small-capacity wells (Wang and Huang 2002). Surprisingly, none of the many farmers we interviewed in 2001—both formally and informally—mentioned any of these factors, and instead asserted that pumping rates had always increased. Five farmers interviewed together estimated irrigation pumping rates for wheat and maize had increased from about 300 mm/year in the 1970s to about 550 mm/year in recent years. They noted that pumping rates may have decreased briefly during the 1980s due to declining water levels, but increased again after the old wells were replaced.

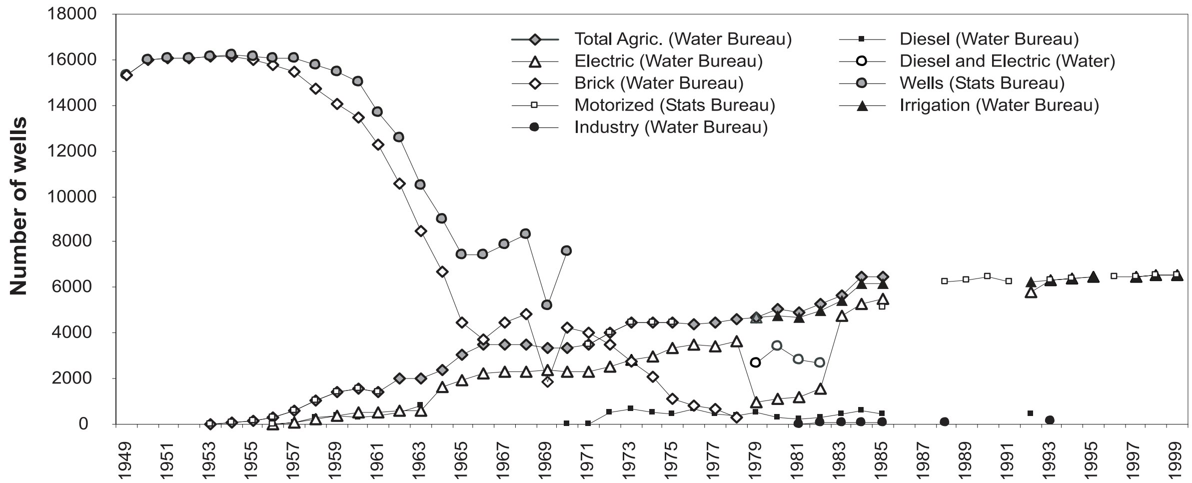
The accuracy of pumping data reported by the Water Conservation Bureau (figure 4.3) may be hampered by a lack of general participation in the well permitting system. According to Water Conservation Bureau officials (Li Suoyi, Director, Water Resources Division; Li Jixiang, Director, Rural Water Division; and Li Jiancuan, Deputy Director, Luancheng County Water Affairs Bureau, personal communication, 2001), every prospective new well owner in Luancheng County must obtain a permit before drilling. However, farmers report that most new wells are installed by private well drillers rather than by the Bureau drilling team because private drillers are generally less expensive, do not require labor contributions from farmers, and, notably, do not obtain permits from the Bureau (Yang Shufen, Zhang Cun Village Leader, Luancheng County, personal communication, 2001). If Bureau personnel rely on new well permits as the basis for their pumping statistics, then pumping probably has been under-reported, at least since the appearance of private well drillers in the early 1980s.

Many researchers have considered the number of wells as an alternative to pumping data (e.g., Kramer and Zhu 1989; Lou and Chen 1985; Xu 1990; Yang and Zehnder 2001). Figure A1 shows the number of wells in Luancheng County reported by two Bureaus, the Shijiazhuang Water Conservation Bureau and the Shijiazhuang Statistics Bureau, for 1949-2000.[11] Although reporting categories evidently changed, overall the number of mechanized wells generally increased over time.

But how accurately does the number of wells represent the quantity of withdrawals? Least-

[11]These agencies administer Shijiazhuang Prefecture, which includes Shijiazhuang City, Luancheng County, and 16 other counties of Hebei Province.

FIGURE A1.
Indicators of water use in Luancheng County—number of wells, 1949-1999.



Note: Data series are named according to reporting categories used by Water Bureau and Statistics Bureau.

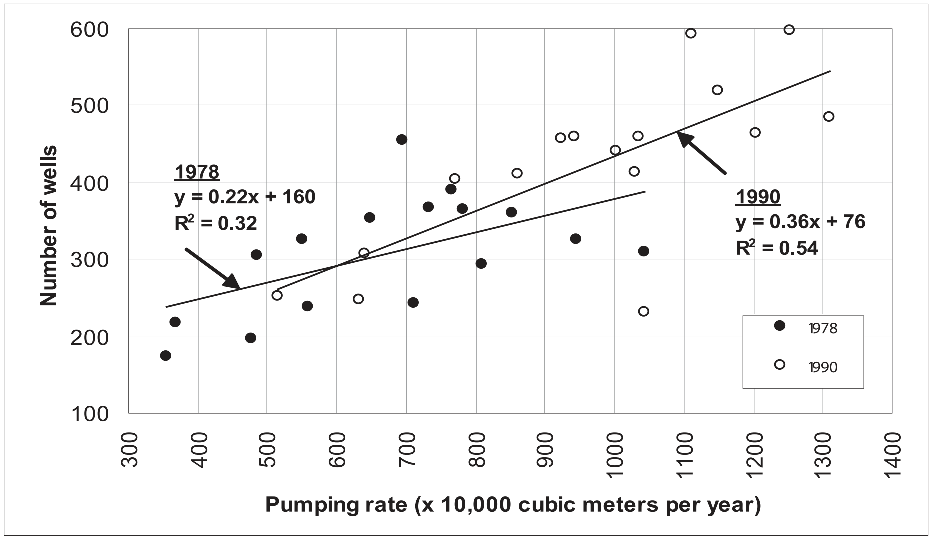
Sources: "Water Bureau" data from Shijiazhuang Water Conservation Bureau (1949-1999); "Stats Bureau" data from Shijiazhuang Statistics Bureau (1949-1999).

squares regression of the number of wells against the quantity pumped from every village in Luancheng County (Luancheng County Natural Resources Survey Team 1979) yields R^2 values of 0.3 for 1978 and 0.5 for 1990 (figure A2). The poor correlation may be due in part to false reporting of new wells. In recent years, the number of wells may have been under-reported. In the past, the number of wells was often over-reported in order to procure government subsidies. A more fundamental issue, however, is that wells differ according to pumping capacity. During the transition from higher- to lower-capacity wells in the late 1970s to the early 1980s, the low correlation between well number and pumping quantity is not surprising. Even today, well pumps sold in Luancheng County have power ratings ranging from 200 to 400 hp. Regardless of the pumping rate "number of wells" statistic makes no claims as to whether those wells actually function (James Nickum, personal communication, 2001). For all of these reasons, it is clear that the number of wells is not a reliable surrogate for the quantity of water pumped.

Another alternative water-use data surrogate might be the statistics that document the expansion and contraction of irrigated land, which are among the most widely available data with the longest continuous periods of record. Ostensibly, this statistic should correlate at least nominally with the amount of water extracted from aquifers for irrigation. Because the irrigated-land data set is both available and complete, it is often used as an indirect indicator of water use. However, the connection between irrigated area and water use is indirect at best. Different crops use different quantities of water. Even if crop varieties are considered, differences in irrigation and water-conservation practices obscure any correlation. Intercropping and multicropping further complicate the analysis. Most importantly, the data are notoriously inaccurate (Nickum 1995; Stone 1993; Tuan 1998).

Even when two agencies publish what are presumably identical data, the figures rarely correspond (Nickum 1995). As a case in point, figure A3 shows irrigated-area data for Luancheng County reported by the Shijiazhuang

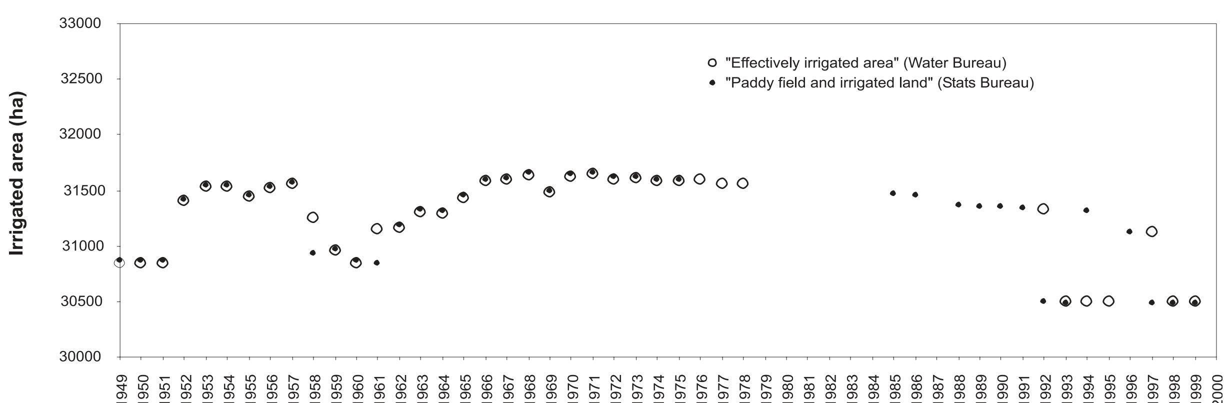
FIGURE A2.
Relationship between groundwater pumping and total number of wells by village in Luancheng County, 1978 and 1990.



Sources: Luancheng County Natural Resources Survey Team 1979; Luancheng County Water Policy and Integrated Water Resources Management Office 1993.

Water Conservation Bureau and by the Shijiazhuang Statistics Bureau. Even if the data discrepancies could be resolved, there exists no logical explanation for the fluctuations reported for the 1990s (figure A3). Moreover, neither reporting agency distinguished between manual irrigation, practiced until the 1970s, and the far more efficient mechanized irrigation that was practiced thereafter. Questions of data accuracy plague any analysis that relies upon irrigated-land statistics, but are especially troublesome when the target of the analysis, water use, is only indirectly related to the data. Thus, like well-number data, irrigated-land data have inherent shortcomings that render them inadequate surrogates for water use.

FIGURE A3.
Indicators of water use in Luancheng County—irrigated area, 1949-1999.



Sources: "Water Bureau" data from Shijiazhuang Water Conservation Bureau (1949-1999); "Stats Bureau" data from Shijiazhuang Statistics Bureau (1949-1999).

Furthermore, water use is not limited to groundwater. Since 1956, farmers in the western part of Luancheng County have diverted water from Jiao He wastewater canal to their fields for irrigation (Luancheng County Chronicle Compilation Committee 1995). At first, the wastewater was applied only to a small area within about 10 km of Shijiazhuang City, but by the 1990s, its use had spread to the entire length of the county (figure 5). All industrial and municipal wastewater and storm-flow from at least an 80-km^2 area of Shijiazhuang City—at least 120-140 million m^3/year (Zhang et al. 2000)—drains into the canal.[12] Because 80 percent of this discharge is untreated, environmental regulations forbid its use for irrigation. It is this legal stipulation that makes reporting of wastewater use awkward. According to the Jiao He Water Management Agency, the wastewater is never used for irrigation (Xing Yue, Director of Jiao He Water Management, Luancheng County, personal communication, 2001). According to the County Agricultural Bureau, about 2,700-3,300 ha are irrigated with wastewater, but only in October and March (Cao Zhenjia, Senior Agricultural Scientist, LC County Agricultural Bureau, personal communication, 2001). According to the County Water Affairs Bureau, the wastewater is used in October and March, but only along a narrow strip adjacent to the canal (Li Suoyi, Director, Water Resources Division, Luancheng County Water Affairs Bureau, personal communication, 2001). Although figure 5 clearly shows that the wastewater-irrigated area has about doubled since the late 1970s (Shijiazhuang City Bureau of Agriculture 1998), the County Agricultural Bureau maintains that the area has declined since about 1980 (Cao Zhenjia, Senior Agricultural Scientist, LC County Agricultural Bureau, personal communication, 2001). In March and June 2001, we observed widespread application of wastewater in an area roughly corresponding to that delineated by the County Agricultural Bureau. Farmers using the wastewater reported having no alternate source of irrigation water. They explained that not only are wastewater diversions unregulated, but that they are actually encouraged by government-constructed infrastructure (distribution canals shown in figure 5, as well as underground pipes and siphons) at no cost to farmers.

For our groundwater balance analysis (Kendy et al. 2003c), we calculated the quantity of wastewater applied based on irrigation data. Shijiazhuang Water Conservation Bureau (1949-1999) reports “groundwater pumping for irrigation”, “groundwater irrigated area”, and “surface-water irrigated area” annually. For every year, the reported “groundwater irrigated area” is equal to the reported “effective irrigated area” and the reported “surface-water irrigated area” is zero. There are two ways to interpret the “groundwater pumping for irrigation” figures. Either they represent groundwater withdrawals or they represent all applied irrigation. Because part of the county is actually surface-water (wastewater) irrigated, it is impossible for them to represent both. We assume they represent all irrigation, and that actual groundwater withdrawals for irrigation are the reported values minus irrigation water supplied by Jiao He wastewater canal. This assumption is consistent with annual per-well irrigation capacities for Luancheng County calculated from the Water Conservation Bureau data, which consistently exceed those calculated for Shijiazhuang Prefecture; the wastewater-irrigated area can account for the difference. Moreover, the reported irrigation quantities (in m^3) for recent years are consistent with normal irrigation practices (Kendy et al., 2002b) if they are distributed over the entire county area, but are excessive if distributed only over the actual groundwater-irrigated area.

[12] According to the Luancheng County Water Policy and Integrated Water Resources Management Office (1993), the drainage area is 168.5 m^2 and the discharge in 1991 was 320 million m^3. According to the Jiao He Water Management Director (personal communication), the drainage area is 113 km^2.

ANNEX 2

Water-Balance Calculation Methodology

Kendy et al. (2003a, 2003b, and 2003c) describe in detail the methods used to calculate the groundwater balance of Luancheng County. This annex briefly summarizes these methods.

Prior to this study, groundwater recharge to the aquifers underlying the North China Plain, including Luancheng County, was poorly understood. Kendy et al (2003a) introduced a one-dimensional soil-water balance model to calculate daily precipitation- and irrigation-generated areal recharge and actual evapotranspiration from commonly available crop and soil characteristics and climate data. In addition, the model calculates daily soil-moisture content for each user-defined soil layer. Inherent assumptions are that water flows vertically downward under a unit gradient; infiltration and evapotranspiration are separate, sequential processes; evapotranspiration is allocated to evaporation and transpiration as a function of leaf-area index and is limited by soil-moisture content; and evaporation and transpiration are distributed through the soil profile as exponential functions of soil and root depth, respectively.

Kendy et al. (2003a) calibrated this simple model by adjusting soil-property input until model-calculated water content of 11 soil-depth intervals from 0 to 2000 mm satisfactorily simulated measured water content of loam soil at four sites in Luancheng County over three years (1998-2001) and model-calculated evapotranspiration compared well with that measured by a large-scale lysimeter. Each 50 m^2 site was identically cropped with winter wheat and summer maize, but received a different irrigation treatment. To test the model, twelve additional sites were simulated successfully.

The model (Kendy et al. 2003a) is particularly suitable to areas like the North China Plain, which have little topographic relief, relatively deep water tables, and insignificant snowmelt, and where available data are limited to the basic climate, soil and crop information typical of major agricultural areas. Compared to other simple soil-moisture models, the model better simulates drainage during prolonged periods between precipitation or irrigation events. The simulation of daily soil-moisture content depends on accurate characterization of soil properties, which is especially challenging for the heterogeneous alluvial settings for which the model is otherwise most suited. Thus, use of model results is best restricted to the seasonal or annual estimates of recharge and evapotranspiration needed for long-term water management.

Kendy et al. (2003b) used the calibrated model (Kendy et al. 2003a) to quantify historical areal groundwater recharge from irrigated cropland to unconfined aquifers underlying Luancheng County for 1949-2000. Natural, pre-irrigation conditions also were simulated. To simplify the simulations, historical agricultural production was modeled as if wheat, maize, vegetables, cotton, sweet potato and millet were the only crops grown and that these crops covered the entire reported cultivated area. Seepage from the 2-m soil profile was assumed to recharge the aquifer immediately, regardless of the water-table depth.

Data input was acquired from a variety of sources, including Luancheng County Meteorological Bureau (climate), Luancheng Agro-Ecological Research Station of the Chinese Academy of Sciences (climate), Shijiazhuang

Water Conservation Bureau (irrigation) and Shijiazhuang Statistics Bureau (land use). Soil characteristics, root depths, leaf-area-indexes, planting and harvest dates and irrigation practices were obtained from other studies and from interviews with local farmers and agricultural researchers.

The model was run six times for 1949-2000, with each run representing a different combination of summer and winter crops: (1) winter wheat and sweet potato, (2) winter wheat and maize, (3) winter wheat and vegetables (1998-2000 only), (4) winter fallow and cotton, (5) winter fallow and millet and (6) winter fallow and vegetables. After calculating annual recharge for each crop combination, the results were combined and weighted by the annual areas planted in each crop combination to determine total annual areal recharge to aquifers beneath Luancheng County. Model-calculated recharge rates ranged from 50 to 1,090 mm/year.

To independently check these results, simple water balances based on the model results were compared to water levels measured in an observation well at Luancheng Agro-Ecological Research Station (figure 8). Assuming a specific yield of 0.2 m/m, Kendy et al. (2003b) showed that the difference between annual groundwater pumping and model-calculated recharge accounts for the approximately 1 m/year water-table decline beneath Luancheng County. Good agreement between measured and model-based water levels indicates that the model results are reasonable.

Although this simple, one-dimensional model of vertical flow seemed to explain the groundwater declines, lateral flow components also needed to be considered. Therefore, Kendy et al. (2003c) calculated complete, annual groundwater balances of Luancheng County under predevelopment conditions and for 1949-2000, using the annual recharge rates calculated by Kendy et al.(2003b). These groundwater balances also account for the effects of stream diversion, urbanization, irrigation and climate changes over time.

Kendy et al. (2003c) used MODFLOW, a finite-difference groundwater flow modeling program (McDonald and Harbaugh 1988), as a means to calculate annual groundwater balances by quantitatively synthesizing the available hydrogeologic data and interpretations into one coherent framework. Inputs to MODFLOW include aquifer geometry, boundary conditions, hydraulic characteristics and other parameters that describe the aquifer system. Groundwater heads and flows constitute model output.

The aquifer beneath Luancheng County was modeled as a single layer, discretized into 507 model cells. Each cell was 1 km^2 in area. Cell thicknesses ranged from about 40 m in the west to about 110 m in the east, according to various maps and geologic reports. The aquifer geometry was simulated identically for both steady-state (predevelopment) and transient (1949-2000) models.

Hydraulic characteristics and boundary conditions (evapotranspiration from the water table; river stages, including that of Jiao He wastewater canal; groundwater pumping, and groundwater heads along the county borders) were determined on the basis of numerous maps, reports and databases. Modeled hydraulic conductivity ranges from 80 to 150 m/day; specific yield is 0.2 throughout the model. Areal recharge from irrigated cropland was input exactly as reported by Kendy et al. (2003b). Areas irrigated by wastewater from Jiao He wastewater canal were modeled with the same areal recharge rates as groundwater irrigated areas, but without any discharges to groundwater pumping wells. Recharge inputs also accounted for industrial and domestic groundwater uses.

Model input was adjusted to achieve a good match between model output and several calibration targets. These targets included estimated seepage from natural rivers and from Jiao He wastewater canal, estimated discharge to springs and evapotranspiration, the timing of the groundwater flow reversal along the northern county boundary and measured heads in seven observation wells.

The calibrated model simulates every important temporal and spatial change in Luancheng County's groundwater balance: the cessation of inflow from natural streams, concurrent with the initial decline in outflow to springs and evapotranspiration; the onset of groundwater pumping, foretelling the cessation of outflow to springs and evapotranspiration; the flow reversal along the boundary with Shijiazhuang; and increasing inflows of urban wastewater. Yet, ultimately, the full groundwater balance accounting based on this complex model supports the simple model presented in Kendy et al. (2003b), which attributes water-table declines solely to crop evapotranspiration. Other flow components, such as seepage from Jiao He wastewater canal and lateral groundwater discharge to the Shijiazhuang City cone of depression, have balanced each other. Thus, the conclusion remains that because crop evapotranspiration constitutes the main regional outflow from the North China Plain, an eventual shift from agriculture to other, less consumptive water uses will be likely to play a crucial role in any long-term, integrated approach to sustainable water use.

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FUTURE HARVEST
IWMI is a Future Harvest Center supported by the CGIAR

ISSN 1026-0862
ISBN 92-9090-517-4