HYDROLOGICAL PROCESSES
Hydrol. Process. **18**, 2289–2302 (2004)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.5529

Groundwater recharge from irrigated cropland in the North China Plain: case study of Luancheng County, Hebei Province, 1949–2000

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Abstract:

Effective management of limited water resources in the North China Plain requires reliable calculation of historical groundwater balances at local, sub-watershed scales. These calculations typically are hindered by poorly constrained recharge estimates. Using a simple soil-water balance model, we independently calculated annual recharge from irrigated cropland to unconfined alluvial aquifers underlying Luancheng County, Hebei Province, in the western part of the North China Plain, for 1949–2000. Model inputs include basic soil characteristics and daily precipitation, potential evapotranspiration, irrigation, crop root depth, and leaf-area index; model outputs include daily actual evapotranspiration and areal groundwater recharge. Results indicate that areal recharge is not a constant fraction of precipitation plus irrigation, as previously assumed, but rather the fraction increases as the water inputs increase. Thus, model-calculated recharge rates range from 5 to 109 cm year^{-1}, depending on the quantity of precipitation and irrigation applied. The important implication is that, because this drainage recharges the underlying aquifer, improving irrigation efficiency by reducing seepage does not save water. This explains why successful efforts to reduce groundwater pumping for irrigation have had no effect on water-table declines. So long as crop cover is extensive and all crop-water requirements are met—which has been the case in Luancheng County since the 1960s—groundwater levels will continue to decline at a steady rate. Potential solutions include reducing the irrigated area, reintroducing fallow periods, and shifting water from agriculture to other, less consumptive uses. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS recharge; water balance; evapotranspiration; irrigation; drainage; North China Plain

INTRODUCTION

Although China's recorded irrigation history dates back to 598 BC (Wang, 1991), until recently irrigation was never important on most of the North China Plain (Huang, 1988; Nickum, 1988; Chinese Hydraulic Engineering Society, 1991). For centuries, farmers produced two or three rainfed crops every 2 years. Only since the advent of mechanized wells in the past 40 years has continual cropping been possible throughout the region (Yang, 1991).

The outstanding gains in agricultural production have not come without costs. Since pumping began, groundwater levels have declined, indicating that water use exceeds natural replenishment rates. In recent years, adverse impacts of the continued declines have raised international concern. These impacts include land subsidence, salt-water intrusion, and municipal water shortages (Chen, 1992; Zhang and Zhang, 1995; Liu *et al*., 2001).

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Received 20 December 2002
Accepted 30 July 2003

Attempts to arrest the declines have focused on technical approaches to save water. For example, researchers in the late 1970s encouraged farmers to reduce irrigation, assuring them that crop yields would not suffer. Accordingly, farmers significantly decreased groundwater pumping, yet water levels continued to decline. In the 1980s, thousands of irrigation ditches were lined to prevent seepage. Immediately, transmission losses declined and groundwater pumping further decreased. Still, water levels continued to decline. To this day, county water-management efforts centre on replacing flood irrigation with sprinkler and drip systems, lining canals and ditches, and replacing irrigation ditches with underground pipes in attempts to reverse the trend of declining groundwater reserves.

So, the experience of the previous decades shows that reducing groundwater pumping alone is an insufficient requisite for saving water. To understand why, all components of the groundwater balance must be considered. Owing to distinct hydrogeologic and socio-economic conditions, water shortages are localized (Zhu and Zheng, 1983; Nickum, 1998). Although the Chinese are not averse to transferring large quantities of water from place to place, political considerations dictate that the majority of water-management decisions are made and carried out at local, rather than regional levels of government (Lohmar *et al.*, 2001). Therefore, it is local groundwater balances that are of utmost importance for water management.

Unfortunately, local groundwater balances are difficult to assess. In the North China Plain, where the land surface is nearly level and diversions transport water across topographic divides, local watershed boundaries are ill defined. Moreover, excessive localized pumping has created vast cones of depression, so groundwater divides no longer underlie surface-water divides. Therefore, at the local scale, watershed boundaries are of no practical use for water-balance calculations.

Whereas watershed-scale calculations are constrained by precipitation inputs, local groundwater balances at the sub-watershed scale include important lateral inflows and outflows. Darcy's law is used to compute these subsurface flows, but the extreme heterogeneity of the alluvial deposits that compose North China Plain aquifers, combined with the lateral discontinuity of those deposits, renders these calculations imprecise. A reasonable range of transmissivity estimates can generate inflow and outflow estimates that range over orders of magnitude. As a result, detailed water-balance analyses of local areas within the North China Plain are hindered by unconstrained flow estimates. Elsewhere, hydrogeologists overcome this limitation by measuring baseflow, or groundwater discharge to streams. But water levels in the North China Plain have declined to the extent that baseflow ceased long ago. Therefore, potentially the most precise check on groundwater balance calculations is unavailable.

Compared with other components of the water balance, the Chinese consider areal recharge to be relatively well constrained. Traditionally, hydrogeologists estimate areal recharge on the basis of water-table rises, which do not discriminate between lateral and areal sources. Once determined, the infiltration coefficient, or the fraction of precipitation that becomes areal recharge, is used under all circumstances, regardless of the quantity of precipitation or irrigation applied. Previous water-balance assessments of the North China Plain have followed this procedure (e.g. Luancheng County Natural Resources Survey Team, 1979; Luancheng County Water Policy and Integrated Water Resources Management Office, 1993).

To check the assumption of a constant infiltration coefficient independently, we developed and tested a simple, one-dimensional soil-water balance model that determines areal recharge and actual evapotranspiration from precipitation, irrigation, potential evapotranspiration, and crop-growth data (Kendy *et al.*, 2002). Three-year simulations of instrumented plots of winter wheat and summer maize indicated that recharge varied from year to year, depending on the quantity and temporal distribution of precipitation and irrigation. In general, the smaller the inputs, the smaller was the fraction that became recharge. This relationship is especially important in places like the North China Plain, where both irrigation and precipitation vary considerably from year to year.

This paper describes an application of the model to quantify historical areal groundwater recharge from irrigated cropland to unconfined aquifers underlying Luancheng County, Hebei Province (Figure 1). The analysis begins in 1949, at the founding of the People's Republic of China, and extends to 2000. Natural, pre-irrigation conditions are also examined. By applying this model to a representative local area of the North

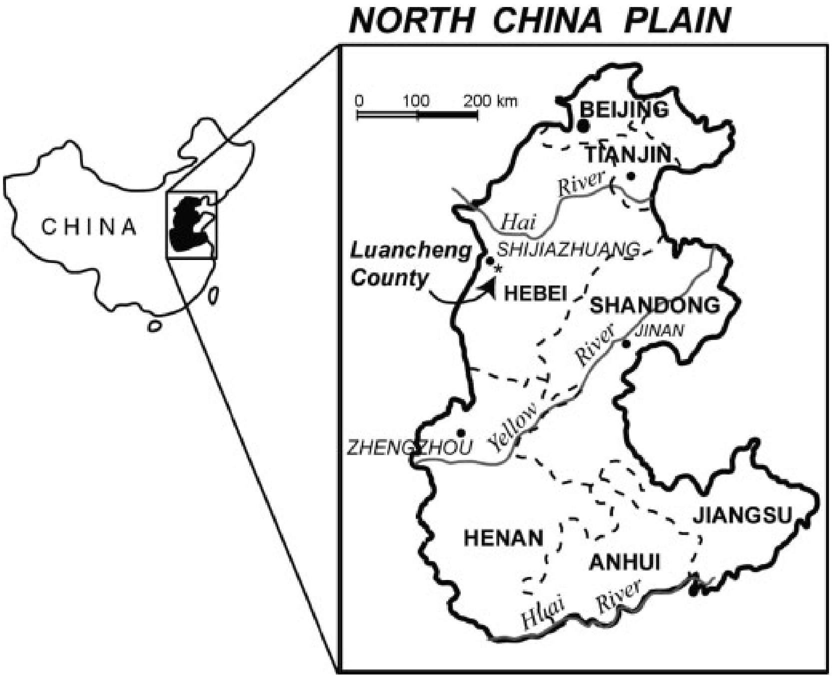

Figure 1. Location of Luancheng County and the North China Plain

China Plain, we hope to demonstrate that areal recharge can be determined independently, thus providing an important constraint on the historical water-balance calculations needed to manage limited water resources effectively.

STUDY AREA

Luancheng County typifies the North China Plain (Table I), particularly the western part of the plain, where favourable hydrogeologic conditions have allowed for intensive groundwater development. Average monthly temperatures range from about $-4\,^{\circ}C$ in January to $25\,^{\circ}C$ in July. Most of the 461 mm of annual rainfall occurs during the humid summer months, with very little during spring and autumn, and even less during the cold, dry winters (Luancheng County Meteorological Bureau, unpublished data, 1971–2000). Groundwater supplies the deficit between rainfall and the water required for continual cropping. The Quaternary-age aquifer system underlying the county consists of laterally discontinuous layers of alluvium and reworked loess (Luancheng County Water Policy and Integrated Water Resources Management Office, 1993). The potentiometric surface is about 30 m below the land surface, or about 25–27 m below the water table of the early 1960s. Groundwater levels typically decline about 1–1·5 m from September to June, then rise about 0·5–1 m during July and August, when monsoon rains fall and withdrawals for irrigation decrease (Figure 2). This annual rise is generally attributed to subsurface lateral inflow, rather than to areal recharge. The consensus among many local hydrogeologists is that, under current conditions, areal recharge is non-existent except during extreme precipitation events.

Land and water use in Luancheng County are primarily agricultural. In addition to winter wheat and summer maize, the county is also an important producer of vegetables, fruit, soybeans, and sorghum (Shijiazhuang Statistics Bureau, issued annually; see Shijiazhuang Statistics Bureau (2000) for details). The loam soils have bulk densities of about 1·4 to 1·6 g cm^{-3}, effective porosities of about 40–50%, and saturated hydraulic

Table I. Comparison 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 (%)	1[e]	1[d]
Aquifer material	Alluvium	Alluvium
Principal crops	Wheat, maize, cotton[d]	Wheat, maize, cotton[b]
Grain yield (kg ha^{-1})	∼5000[f]	7291[g]
Water source	Ground water, surface water	Ground water, municipal wastewater
Total land cultivated (%)	50[a]	81[g]
Cultivated land irrigated (%)	56[a]	99[g]
Population	214 000 000[a]	361 279[g]
Population density (km^{-2})	669	953

[a] Liu *et al*. (2001).
[b] Shijiazhuang Statistics Bureau (issued annually; see Shijiazhuang Statistics Bureau (2000) for details); 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 (1988).
[d] Hebei Province Survey and Mapping Bureau (1999).
[e] Yang (1991).
[f] Based on data for Fuyang River basin data (J.-X. Wang, personal communication).
[g] Shijiazhuang Statistics Bureau (2000).

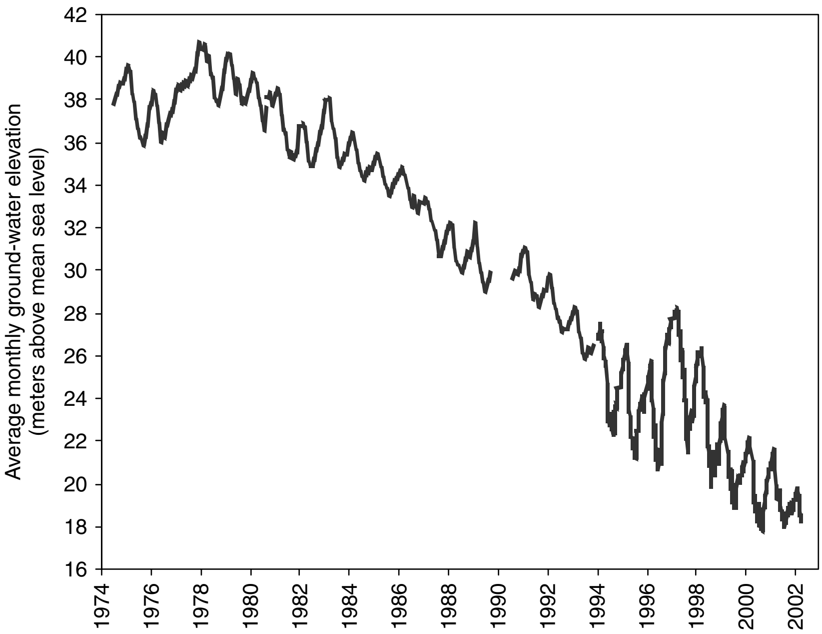

Figure 2. Hydrograph showing historical water-table elevations beneath Luancheng Agro-Ecological Research Station (Chinese Academy of Sciences), Luancheng County, Hebei Province, 1974–2000. Land-surface elevation is 50.27 m above mean sea level

conductivities of about 0·001–1 m day^{-1} (Zhang and Yuan, 1994; Zhang *et al*., 2001). Technical and political developments over the past 50 years have fostered considerable changes in the county's agricultural systems, as evidenced by its cropping and irrigation history (Figure 3).

MODEL DESCRIPTION

The one-dimensional soil-water balance model used for this analysis calculates precipitation- and irrigation-generated areal recharge and actual evapotranspiration from commonly available crop and soil characteristics and climate data (Kendy *et al*., 2002). In addition, daily soil-moisture content is calculated 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

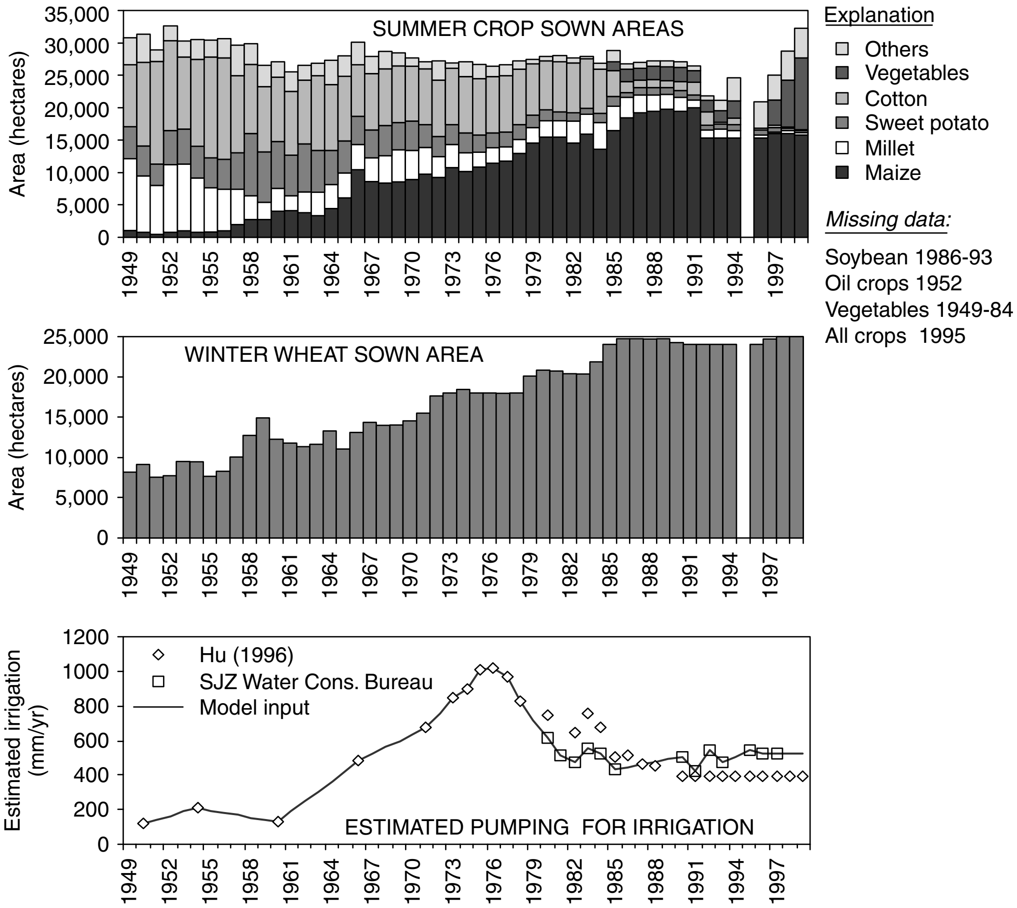

Figure 3. Published cropping and irrigation history of Luancheng County, 1949–99. Crop areas are from Shijiazhuang Statistics Bureau (issued annually; see Shijiazhuang Statistics Bureau (2000) for details). 'Other' summer crops include orchards, sorghum, oil crops, and soybeans. Irrigation estimates are by Hu (1996) and the Shijiazhuang Water Conservation Bureau (issued annually). 'Pumping' in the 1950s was primarily hauling, rather than pumping, from shallow, brick-lined wells. When available, the Water Conservation Bureau's estimates were used as model input because they concur with local farmers' estimates and with irrigation measurements at Luancheng Agro-Ecological Station

evaporation and transpiration are distributed through the soil profile as exponential functions of soil and root depth respectively.

Several processes are modelled during each daily time step. First, precipitation or irrigation is added to the top layer, and then distributed downward in a simple 'tipping bucket' routine. Next, water is redistributed by solving for downward flux (infiltration) from each layer. Flux from the bottom layer may be considered groundwater recharge. Evapotranspiration from each layer is then determined. Evapotranspiration is separated into evaporation and transpiration, which is controlled by the crop-growth indicators, root depth, leaf-area index, and soil-moisture content. Finally, the new soil-moisture content is calculated as the water-balance residual.

Calibration was achieved by adjusting the soil-property input until the model-calculated water content of 11 soil-depth intervals from 0 to 200 cm satisfactorily simulated the measured water content of loam soil at four sites in Luancheng County over 3 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, 12 additional sites were simulated successfully (Kendy *et al.*, 2002).

The model 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 with other simple soil-moisture models, the model simulates drainage better 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 otherwise is 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.*, 2002).

MODEL APPLICATION

To understand how cropping and irrigation practices have affected areal groundwater recharge over time, we simulated the historical soil-water balance of Luancheng County over the period 1949–2000, using the calibrated model described by Kendy *et al.* (2002). We also simulated natural, pre-irrigation conditions. To simplify the simulations, we modelled the historical agricultural production as if wheat, maize, vegetables, cotton, sweet potato, and millet were the only crops grown and those crops covered the entire reported cultivated area.

Model inputs include basic soil characteristics (saturated hydraulic conductivity, wilting point, and effective porosity) and daily crop-root depth, leaf-area index, precipitation, potential evapotranspiration, and irrigation. Eleven soil layers were modelled, extending from the land surface to a depth of 2 m. Soil characteristics are detailed in Kendy *et al.* (2002). Daily root depths and leaf-area indices were obtained from a variety of sources, and typical local planting, harvest, and irrigation dates were assumed (Table II).

Climate data were obtained from Luancheng County Meteorological Bureau (1963–83) and Luancheng Agro-Ecological Station of the Chinese Academy of Sciences (1984–2000). Potential evapotranspiration was approximated as $0{\cdot}7\times$ Class-A pan evaporation (Kendy *et al.*, 2002). Daily precipitation and pan-evaporation data were available for Luancheng County (1971–2000) and for adjacent Zhao County (1963–70). Daily data for 1955–62 were synthesized by distributing monthly values reported for adjacent Shijiazhuang City (Figure 1), 1955–62, according to daily precipitation and evaporation distributions reported for Zhao County, 1963–70. Missing pan-evaporation data for 21 January 1963–2 August 1965 were synthesized by replicating data from 21 January 1977–2 August 1979, which had similar rainfall patterns. Likewise, missing pan-evaporation data for 1 September 1966–31 March 1970 replicate 1 September 1970–31 March 1974. Model input for pre-1955 climate, for which no actual data are available, replicate year 1974, when the

Table II. Typical planting and harvest dates, maximum root depth, maximum leaf-area index (LAI), and irrigation requirements of the major crops grown in Luancheng County

Crop	Planting date[a]	Harvest date[a]	Maximum root depth (m)	Maximum LAI	Irrigation requirement
Winter wheat	5 Oct	10 June	2[b]	5·7[f,g]	7 Oct (8 cm), 1 Dec (4 cm), 4 Apr (10·4 cm), 24 Apr (10·2 cm), 9 May (10·4 cm)[a,j]
Maize	25 May	20 Sept	1·8[b]	4·3[f]	15 June (4 cm), 11 Aug (8·2 cm)[a,j]
Millet	1 May	5 Sept	1·4[e]	5·0[h]	2 May (7·0 cm)[e]
Cotton	22 Apr	18 Oct	1·2[d]	4·4[i]	24 Apr (8 cm), 15 July (5 cm)[e]
Vegetables	22 Apr 11 June	24 Oct 1 Oct	0·6[e]	3·2[h]	As needed, based on monthly climate[e]
Sweet potato	11 June	4 Oct	0·6[e]	4·1[h]	15 June (6·0 cm), 30 Aug (6·0 cm)[e]
Fallow	—	—	0·05	0·1	None

[a] Based on interviews with: Cao Zhenjia, Senior Agricultural Scientist, Luancheng County Agricultural Bureau; Zeng Jianghai, retired Director of Luancheng Experimental Station, Chinese Academy of Sciences; and Zhang Xiying, Professor, Shijiazhuang Institute of Agricultural Modernization, Chinese Academy of Sciences, 2001.
[b] Zhang (1999).
[c] Unpublished measurements at Luancheng Station (X.-Y. Zhang, personal communication, 2001).
[d] Li (1979), Cotton Institute (1983).
[e] Vegetables typically are irrigated more on an as-needed basis than the other crops, which are more rigidly scheduled. Therefore, we used irrigation-scheduling software (Smith *et al*., 1998) to generate model input for vegetable irrigation for 1984–2000. For earlier years, when the vegetable crop area was almost negligible, the average calculated annual irrigation (34 cm) was used, represented by the year 1993.
[f] Zhang *et al*. (2002), Wang *et al*. (2001).
[g] Liu *et al*. (1998).
[h] Fischer *et al*. (2000).
[i] Liu Xiaojing, Professor, Director of Nanpi Eco-Agricultural Research Station, Chinese Academy of Sciences, personal communication, 2002.
[j] Field site 6, Luancheng Station, 1999–2000.

annual precipitation (53·4 cm) closely resembled the long-term average annual precipitation (53·6 cm) (Hebei Province Survey and Mapping Bureau, 1999).

Because the quantity of groundwater recharge depends strongly on the temporal distribution of irrigation, a concerted effort was made to simulate irrigation according to local historical practices. The information available for this purpose is limited to estimated annual groundwater pumping rates and annual land areas sown with each crop (Figure 3). However, historical records do not indicate how annual pumpage was distributed over each growing season, nor how it was allocated between crops. Moreover, some of the records are internally inconsistent. For example, for almost every year, the reported 'total cultivated area' exceeds the sum of the reported areas of individual crops. To resolve the inconsistencies, while maintaining data integrity as much as possible, we based the model input on the following assumptions (Figure 4):

1. Reported areas of wheat, maize, cotton, millet, sweet potato, and vegetables are accurate.
2. 'Winter fallow area' is equal to the 'total cultivated area' minus the 'wheat-sown area'.
3. 'Unreported summer crop area' is equal to the 'total cultivated area' minus the 'sum of reported summer crop areas'. The reported summer crops are maize, cotton, sweet potato, millet, vegetables, soybeans, oil crops, orchards, and sorghum.
4. Maize and sweet potato were always multicropped with wheat, i.e. they were planted on land on which wheat was grown in the same year.
5. Vegetables, cotton, and millet were never multicropped with wheat, i.e. they were planted on land that had lain fallow over the winter.
6. Soybeans, oil crops, orchards, sorghum, and unreported summer crops could be lumped and modelled either as maize (equal to 'wheat area' minus 'sweet potato area' minus 'maize area') or as cotton (equal to 'winter

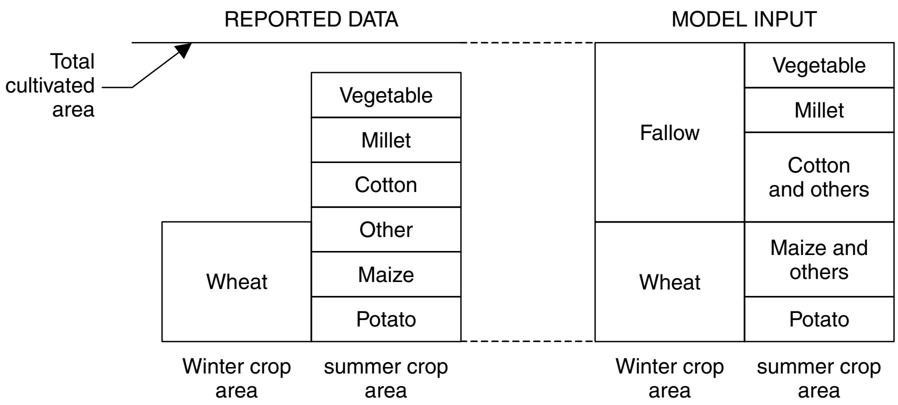

Figure 4. Strategy for interpreting historical land-use data for 1949–97 model input. For each year, the reported areas of wheat, vegetable, millet, cotton, maize, and sweet potato, and total cultivated area, are modelled as reported by the Shijiazhuang Statistics Bureau. Areas of 'other' reported crops (soybean, oil crops, orchards, and sorghum) are combined with the area of unreported corps and modelled as either maize or cotton, depending on whether the crops were multicropped with wheat or planted on winter fallow. In 1998–2000, vegetables were also multicropped with wheat

fallow area' − 'vegetable area' minus 'cotton area' minus 'millet area'). These are designated as 'others' in Figure 4.

7. Missing crop and irrigation data can be linearly extrapolated from years with data, except for vegetable area before 1985, which can be approximated as 2 m^2 per person.

Although water allocation surely varied from place to place, for the historical model we assumed that the typical irrigation applications listed in Table II adequately meet crop requirements. Irrigation requirements for maize and wheat were modelled as the actual timing and quantity applied to field site 6 at Luancheng Station in 1999–2000 (Kendy *et al*., 2002). Field site 6 was selected because the quantity applied (55·2 cm) closely represents annual irrigation reported by Shijiazhuang Water Conservation Bureau (52·6 cm in 1998, 1999) and estimated by local farmers (48–60 cm), and the timing was similar to that reported by local agricultural scientists (Table II, footnote a). Water stress was simulated by applying partial or no irrigation, which effectively reduces crop evapotranspiration (Kendy *et al*., 2002). In 1949–52 and 1957–61, when pumping and irrigated-area data indicate that insufficient water was available to meet crop requirements, we prioritized irrigation in the order of wheat, maize, vegetables, cotton, sweet potato, and millet. For example, according to our model input for 1950, wheat, maize, and vegetables received full irrigation, cotton received partial irrigation, and sweet potatoes and millet were rainfed. In all other years, pumping exceeded crop requirements; in the model, we allocated the excess proportionately to all crops. The modelled irrigation applications include conveyance losses, which we assume were equally distributed among all irrigated crops.

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 areas planted in each crop combination to determine total annual areal recharge to aquifers beneath Luancheng County.

To simulate pre-irrigation conditions, an additional 12 year model was run, using precipitation and pan evaporation data from 1974 to represent long-term climate conditions. A 3 year crop rotation was simulated with winter fallow and millet the first year, winter wheat and sweet potatoes the second year, and winter fallow and cotton the third year. No irrigation was applied.

RESULTS

As a 'Model County' for increasing crop yields through groundwater irrigation (Luancheng County Chronicle Compilation Committee, 1995), Luancheng received substantial government assistance for well drilling nearly a decade sooner than other counties. Thus, although the modelling results are unique to Luancheng County, the overall pattern is thought to represent the North China Plain as a whole, albeit with some delay in initial irrigation development.

Figure 5 shows how the model-calculated soil-water balance has responded over the past 50 years to changes in cropping and irrigation practices in Luancheng County. Before irrigation, most crops were rainfed, and all fields were fallowed at least every other winter. Groundwater recharge was small and steady, pulsing only in response to intense rainfall. With the encouragement of government financial and technical assistance, the quantity of groundwater extracted each year for irrigation increased steadily through the 1960s. Almost immediately, most crop requirements were met, as indicated by the levelling off of annual evapotranspiration rates. Continued increases in irrigation allowed farmers to replace winter fallow with winter wheat. To enable this change, farmers substituted long-season summer crops, such as cotton and millet, with maize, which requires a shorter growing season and, therefore, multicrops easily with winter wheat (Figure 3). Well drilling and groundwater pumping continued to increase through the mid 1970s. Under collective water management, irrigation was applied 24 h day^{-1} at its peak. Crop requirements, however, remained steady, as indicated by evapotranspiration rates, and the excess water percolated through fields and recharged aquifers at an accelerated rate. Decollectivization in the late 1970s brought improved irrigation efficiency, precipitating the steady decline to current pumping rates. Drainage through irrigated soils decreased at about the same rate as pumping, so *net* groundwater withdrawals (evapotranspiration) remained relatively constant. Consequently, groundwater levels continued to decline, despite reduced pumping due to increased application efficiency.

To check the model results independently, we compared simple water balances based on the model results with water levels measured in the observation well at Luancheng Station. We assumed that all irrigation water in Luancheng County is obtained from wells and that the specific yield of the aquifer is 0·2 (Lin and Yang, 1991). Figure 6 indicates that the difference between pumping for irrigation and model-calculated recharge agrees well with the observed water levels. In reality, lateral flows across the county boundaries are significant; Figure 6 implies that lateral inflows and outflows may be balanced.

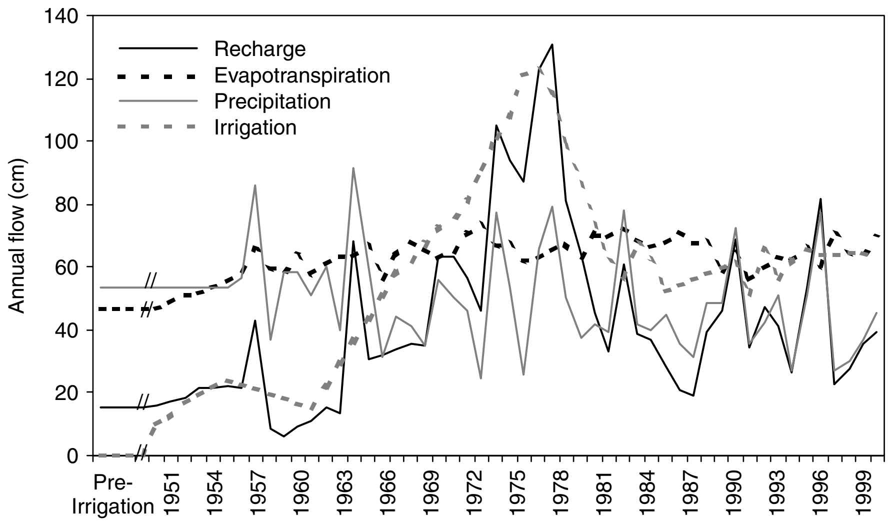

Figure 5. Soil-water balance for cultivated areas of Luancheng County, 1949–2000. Precipitation and irrigation were input to the model; groundwater recharge (drainage from the soil profile) and evapotranspiration were model-calculated

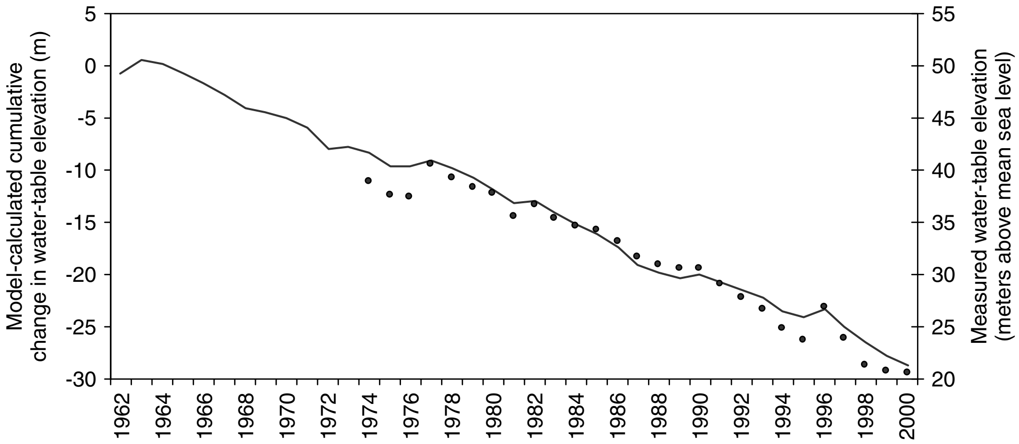

Figure 6. Water-table change due agricultural groundwater use in Luancheng County, 1962–2000. Model-calculated annual water-level changes (line; primary axis) were calculated by subtracting estimated pumping for irrigation (Figure 3) from model-calculated recharge. Measured water-table elevations (dots; secondary axis) represent average December water levels observed beneath Luancheng Agro-Ecological Research Station (Chinese Academy of Sciences)

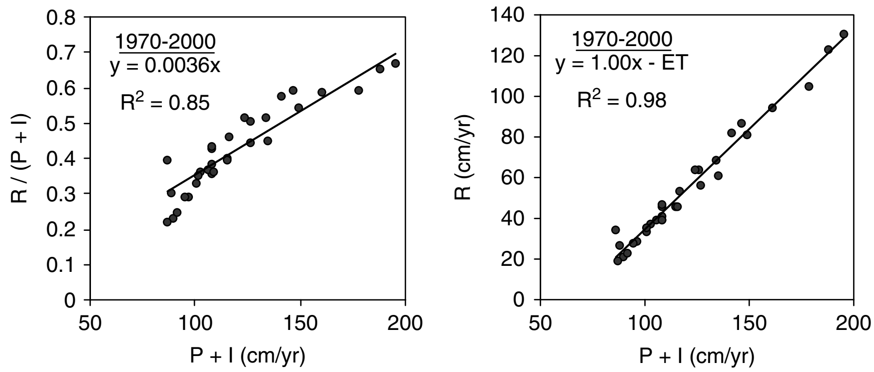

Figure 7. Relationship between model-calculated annual recharge R and precipitation plus irrigation $P + I$, 1970–2000. Average calculated evapotranspiration (ET) is 65.9 cm year^{-1}

Figure 7 shows the relationship between the model-calculated annual recharge R and annual precipitation plus irrigation $P + I$ and the average annual evapotranspiration (66 cm) for 1970–2000, when irrigation consistently met all crop requirements. The empirical equation describing the relationship,

$$R = 1{\cdot}00(P + I) - 66 \qquad (1)$$

has an $r^2 = 0{\cdot}98$ (Figure 7). The plot on the left shows that the correlation between $P + I$ and recharge as a fraction of $P + I$ is much weaker ($r^2 = 0{\cdot}85$). This result is consistent with that found during model calibration and testing: areal recharge is not a constant fraction of $P + I$, but rather the fraction increases as $P + I$ increases (Kendy *et al.*, 2002). The important implication is that, because this drainage recharges the underlying aquifer, improving irrigation efficiency by reducing seepage does not affect water-table elevations.

In contrast, changing cropping patterns can reverse water-table declines. Figure 8 shows cumulative model-calculated water-table changes for five crop combinations, assuming the specific yield of the aquifer is 0·2. Like Figure 6, annual changes in groundwater storage were calculated by subtracting inflow (model-calculated recharge) from outflow (pumping for irrigation) for each crop combination. The results shown in Figure 8

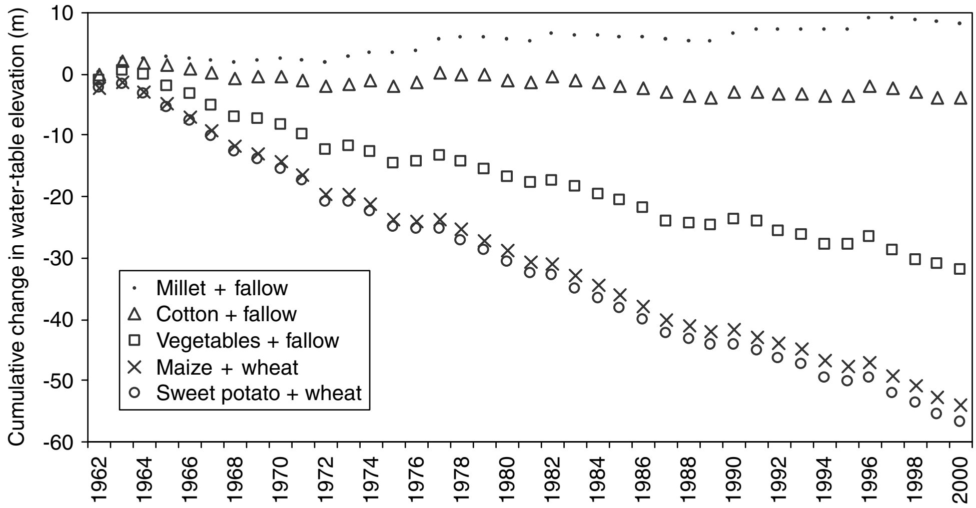

Figure 8. Model-calculated cumulative water-table changes due to five crop combinations, 1962–2000

suggest that if Luancheng County had produced only cotton and millet since 1962, then the water table would have remained stable, had pumping for irrigation been the only influence on groundwater levels. The other three crop combinations use more water than is naturally replenished, as evidenced by negative cumulative changes in water-table elevation. The lesson for future water management is that reintroducing fallow periods and shifting to less water-intensive crops are reasonable approaches for alleviating groundwater declines.

DISCUSSION OF MODEL RESULTS

Although the general patterns revealed by the model are valid, the numeric results should be viewed with caution because they were obtained on the basis of a model that was calibrated to different conditions (1998–2001) than those present in Luancheng County during the application period (1949–2000). First, the model is only calibrated to wheat and maize, and not to the other crop combinations modelled. Second, increases in vegetative production result in increases in evapotranspiration (Burman and Pochop, 1994). In using constant leaf-area indices to calculate historical recharge, we essentially assumed that crop yields have been constant through time, when, in reality, crop yields have increased (Shijiazhuang Statistics Bureau, issued annually; see Shijiazhuang Statistics Bureau (2000) for details). Third, in order to simplify model input, we assumed that any given plot of land was continuously sown in only one of the six crop combinations modelled. In reality, farmers rotated crops and, notably, fallow land from year to year. Consequently, some of the water that our application allowed to build up in fallowed soil would, in reality, have been consumed by a winter wheat crop the following year, rather than recharging the aquifer. Fourth, for this study, all soils in Luancheng County were assumed to be similar to those characterized at Luancheng Station. However, detailed soil maps (Luancheng County Natural Resources Survey Investigation Team, 1980) indicate that about 30% of the county's soils have moisture-retention capacities smaller than that of Luancheng Station's soils. Reducing the saturation moisture content input to the model by 10% results in a 7% decrease in calculated evapotranspiration and a 26% increase in calculated recharge from a wheat and maize field in 1998–2001.

What the model does not reveal, and what still is not clearly understood, is what happens to water between the time it drains from the top 2 m in the soil profile and the time it recharges the aquifer 30 m below the land surface. Water-table observations indicate relatively rapid rises following large rainfall events, probably in response to a combination of areal recharge, lateral recharge, and recovery from pumping for irrigation, which stops during the monsoon. The relative response to each of these impacts varies from year to year. For example, the water-level rise in response to an exceptionally large rainfall in 1996 progressed and dampened from west to east across Luancheng County (Hebei Water Resources Bureau, unpublished data), indicating a strong influence of subsurface lateral inflow from the west.

Still, for long-term planning purposes, the exact timing of groundwater recharge is less important than the quantity of that recharge. Whereas soil-drainage analysis requires an hourly to daily timeframe, groundwater flow operates on longer scales of months to years (Anderson and Woessner, 1992). Thus, regardless of when soil drainage becomes recharge, the model-calculated quantities provide useful constraints on the historical water-balance calculations needed to manage limited water resources effectively. The model's proven ability to simulate soil moisture and evapotranspiration under a wide range of irrigation conditions (Kendy *et al.*, 2002), and the agreement between model-calculated and measured historical water-table declines (Figure 6), lend credence to the model-calculated historical annual recharge.

IMPLICATIONS FOR SUSTAINABLE WATER MANAGEMENT

Both past and present approaches to alleviate groundwater declines in the North China Plain have focused on a single goal, i.e. reducing pumping. Although this goal has been accomplished, the ultimate goal of reversing groundwater declines has not. Model results indicate that the long-term pattern of groundwater recharge has closely followed that of irrigation. After crop-water requirements are met, excess water applied to the land surface simply drains through the soil profile to recharge the aquifer. Short-term perturbations in the recharge pattern are responses to precipitation, which fluctuates greatly from year to year, and periodically generates significant pulses of groundwater recharge. Even without undertaking a complete groundwater analysis, by explicitly modelling recharge through historical crop and irrigation changes we have gained useful insight into why past water-management approaches have been ineffective.

The most important lesson is that so long as crop cover is extensive, that crop water requirements are met, and that precipitation is less than evapotranspiration—which has been the case in Luancheng County since the 1960s—net groundwater depletion from pumping for irrigation will remain stable. That is, groundwater levels will continue to decline at a steady rate. In other areas, reducing non-productive evapotranspiration from fallow lands and reservoirs offers opportunity for water savings. However, Luancheng County no longer has significant fallow land or ponded water. Therefore, the only means to reduce net water consumption for agriculture is to reduce evapotranspiration from crops. This can be accomplished either by reducing crop area (or reintroducing fallow periods) or by reducing irrigation to the extent that the current crops become water stressed. To save enough water to reverse groundwater declines, either approach will lead to the economically unpalatable outcome of reduced crop yields.

Many people believe that replacing open irrigation ditches with underground pipes can reduce evaporation without reducing yields. Already, underground concrete and PVC pipes serve more than 20% of the irrigated land in Luancheng County. Water managers advocate underground pipes because they do not lose water to evaporation. Farmers like them because they can plant crops on top of the pipelines, thereby increasing their total production. Whether the effort and expense of pipe installation results in water savings depends on whether evapotranspiration from the newly created cropland is actually less than from the old ditches. An important factor to consider is that the ditches only carried water periodically, whereas crops transpire continuously from the entire route zone throughout the growing season.

Although sprinkler and drip irrigation have saved water in some arid regions, our results suggest they would have little effect in the North China Plain, where excess flood irrigation eventually recharges the water supply. As long as irrigation supplies crop requirements, the mode of delivery is irrelevant. Sprinklers might even increase evapotranspiration by spraying fine droplets into the arid air. An exception might be precision irrigation of widely spaced fruit trees, which reduces evaporation from the bare soil between trees. A precise comparative analysis between the water-balance impacts of sprinkler, drip, and flood irrigation in cropland overlying unconfined aquifers presents an important topic for future research.

Methods of reducing evapotranspiration are actively being pursued. Crop research is focusing on developing varieties with improved drought resistance so that crops can withstand water stress without reducing yields. Plastic mulch is widely used in the North China Plain to reduce the evaporation component of evapotranspiration. Ongoing research is attempting to quantify the potential water savings (e.g. Zhang *et al*., 2002). However, irrigated crop plantings are extremely dense, so most of the water savings occur during the brief periods between crops, when dry surficial soil layers naturally minimize evaporation. The proliferation of greenhouses may be a promising sign, because the artificially humid and windless environment reduces evapotranspiration (L. D. Albright, personal communication, 2002). But greenhouse construction and maintenance are too expensive to justify their sheltering the entire cultivated area of the North China Plain. Although these approaches are attempting to solve the right problem, it is doubtful that their combined implementation will be sufficient to reduce evapotranspiration significantly. Interbasin water transfers notwithstanding, an eventual shift from agriculture to other, less consumptive water uses will likely play a crucial role in any long-term, integrated path to sustainable water use in the North China Plain.

ACKNOWLEDGEMENTS

Funding for this research was generously provided by: Cornell University East Asia Program China Research Travel Grant; Cornell International Institute for Food, Agriculture, and Development Travel Grant; the Teresa Heinz Scholars for Environmental Research; the International Water Management Institute; and the US Department of Education. Special appreciation is extended Zeng Jianghai, Ma Qijun, Jia Jinsheng, Mao Xuesen, Zhang Xiying, and Liu Xiaojing of the Shijiazhuang Institute of Agricultural Modernization and Wang Jinxia of the Center for Chinese Agricultural Policy for assistance in obtaining and understanding historical information, without which this project would not have been possible. Many thanks also to the numerous farmers and government officials in Luancheng County who kindly agreed to be interviewed for this study. Finally, we are grateful to Christopher A. Scott and David J. Molden of the International Water Management Institute for insightful colleague reviews that substantially improved the quality of this paper.

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