RESEARCH REPORT

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Urban Wastewater: A Valuable Resource for Agriculture A Case Study from Haroonabad, Pakistan

Wim van der Hoek, Mehmood Ul Hassan, Jeroen H.J. Ensink, Sabiena Feenstra, Liqa Raschid-Sally, Sarfraz Munir, Rizwan Aslam, Nazim Ali, Raheela Hussain and Yutaka Matsuno

International Water Management Institute

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Summary

Farming communities in water-scarce regions increasingly practice the use of urban wastewater in agriculture. Untreated urban wastewater is generally considered unacceptable for direct use because of potential health risks. However, in many parts of the world, poor farmers in peri-urban areas use untreated wastewater. This practice is likely to continue in the foreseeable future due to the high investment cost associated with the installation of treatment facilities.

In order to systematically document the advantages and disadvantages of using untreated urban wastewater, a case study was undertaken in Haroonabad, which is a small town in the southern Punjab in Pakistan. Information on costs and benefits associated with wastewater use was obtained by monitoring a group of 20 wastewater farmers and a group of 20 non-wastewater farmers over a one-year period. Water and nutrient applications and the quality of groundwater and soil were investigated in nine fields, of which some were irrigated with wastewater and others with regular canal water. To assess the human health impacts, a comparison was done between a settlement where wastewater irrigation was practiced and one where regular canal water was used.

The greatest benefit for farmers using wastewater was the reliable water supply, which allowed them to grow high-value vegetable crops. However, water and nutrient applications to wastewater-irrigated fields were excessive in relation to the recommended values. From this we can deduce that, with the improved distribution of wastewater, more farmers could benefit from the water and the nutrients it contains. Although there were signs of accumulation of heavy metals in wastewater-irrigated soils, the values did not exceed internationally recommended standards. However, there were negative health impacts, especially in the form of an increased prevalence of hookworm infections among wastewater farmers.

Irrigation with untreated wastewater is practiced in most cities in Pakistan because of its high productivity. Wastewater use also has an indirect benefit associated with the reduction of pollutants discharged into natural watercourses. The study concludes that there is a need to identify methods to prevent or lower the health risks associated with the use of untreated urban wastewater while maintaining or increasing its socioeconomic and environmental benefits under the prevailing social and economic conditions.

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Introduction

The use of urban wastewater in agriculture, which is a centuries old) practice (Asano and Levine 1996) is becoming more important under the increasing scarcity of freshwater resources faced by many arid and semi-arid countries.

There are many advantages in using urban wastewater in agriculture and it can be seen as a combined strategy for:

(Direct benefits)

- conservation of water,
- recycling of nutrients, thereby reducing the need for farmers to invest in chemical fertilizer, and
- provision of a reliable water supply to farmers particularly in low-income dry areas;

(Indirect benefits)

- prevention of pollution of rivers, canals and other surface water that would otherwise be used for the disposal of the wastewater, and
- the disposal of municipal wastewater in a low-cost and hygienic way.

These advantages for farmers, municipalities, and society in general have to be weighed against the disadvantages of using wastewater for irrigation, which are mainly related to the presence of pathogenic enteric microorganisms (bacteria, viruses, and parasites) in the water. These pathogens can pose health risks for the farmers and communities who are exposed to the wastewater, and for the consumers of produce irrigated with wastewater. The main health risk in relation to wastewater irrigation is an infection with intestinal helminths (Mara and Cairncross 1989). Additionally, if the wastewater contains industrial effluent, chemical pollutants such as heavy metals can accumulate in the soil and crops and thereby, pose a health hazard.

These health risks can be greatly reduced by treating the wastewater before using it. However, many of the existing technologies are prohibitively expensive for low-income developing countries. In addition to the high cost of building treatment plants, the cost of utilizing peri-urban land for treatment plants and sewage collection costs are also prohibitive factors.

A further disadvantage is that many of the conventional treatment methods remove the nutrients in wastewater, thus reducing the economic benefits to the users. There are alternative lower-cost treatment technologies such as wastewater stabilization ponds, which are used extensively in mid-income countries, especially in the Middle East. However, the reality is that as much as two-thirds of the wastewater generated in the world receives no treatment at all (Mariño and Boland 1999). A large number of wastewater treatment plants dealing with the other one-third are not properly operated and maintained. For example, less than 10 percent of the existing wastewater treatment plants in Mexico are estimated to be operating satisfactorily (Mariño and Boland 1999).

Many countries have legislation that prohibits the cultivation of vegetables, that are intended for human consumption, with untreated wastewater, but allows, for example, fodder crops. An example is Mexico, a country that makes extensive use of wastewater in agriculture (Scott et al. 2000). Crop restriction can prevent human health problems but has the disadvantage of reducing the economic benefits of using wastewater, as it is the high-value crops like vegetables (that are popular in peri-urban areas), which are the most susceptible to contamination. Besides, like other water-related policies (Prathapar et al. 2001), crop restrictions might not be effectively enforced in a developing-country setting.

Under conditions of water scarcity and weak enforcement of legislation, the use of untreated wastewater is an unplanned, often spontaneous activity, which is practiced by poor farmers in urban and peri-urban areas in many countries around the world (Chanduvi 2000). Wastewater remains and will continue to remain a cheap and reliable source of water and nutrients. The common point of view of researchers, decision-makers, and service providers is that the use of untreated wastewater is unacceptable and can provide benefits only when treatment is provided. This approach may result in a further marginalization of poor wastewater farmers who are unlikely to benefit from the treatment of the wastewater that they use or from the use of alternative water sources any time in the near future given the associated cost of both these methods.

The situation in Pakistan is a case in point. Pakistan has a rapidly growing population, which is expected to increase from 156 million in 2000 to 263 million in 2025 (United Nations Population Fund 2000). By that time, about 50 percent of the population will live in urban centers, the large majority of whom lives in the Indus river basin, which provides water for the largest contiguous irrigation system in the world. An estimated 25-35 million people in the Indus basin live in areas with brackish groundwater and very low rainfall and, therefore, depend on surface irrigation water for all their water needs, including washing, bathing, and drinking (van der Hoek et al. 1999). In most towns in Pakistan, which have a sewage disposal system, the wastewater is used for irrigation. In those cases where wastewater is not used directly, it is disposed of in the most convenient surface water bodies, which often are irrigation canals that serve as the source of drinking water for people further downstream. However, the quantities of wastewater disposed of and used are unknown in most cities.

Table 1 shows the results from a rapid reconnaissance survey carried out in the southern Punjab. In all cases wastewater was untreated, and no regulations existed for what could be grown with wastewater irrigation. In the cities surveyed, vegetables were the most common wastewater-irrigated crops because they fetched high prices in the nearby urban markets. The wastewater was valued by the farmers because of its nutrient content and reliability of supply, and was bought from the municipality in some cases. The general tendency was that a small group of farmers controlled the water, distributing it among themselves and the excess, if any, to others.

The use of untreated wastewater is a widespread and pervasive practice of poor people and, as such, innovative approaches are needed to optimize its benefits and minimize the negative health impacts. However, only after documenting

TABLE 1.
Wastewater use in cities of the southern Punjab, Pakistan.

City	Population[a]	Wastewater-irrigated area (ha)	Crops grown with wastewater
Bahawalpur	408,000	600	Vegetables
Bahawalnagar	111,000	55	Vegetables and fodder
Burewala	152,000	500	Vegetables, wheat, cotton, and fodder
Vihari	94,000	160	Vegetables, wheat, cotton, and fodder
Arif Wala	74,000	300	Vegetables, rice, cotton, and fodder
Haroonabad	63,000	150	Vegetables, cotton, and fodder
Khairpur	27,000	25	Vegetables and fodder
Fort Abbas	35,000	100	Vegetables
Minchinabad	26,000	12	Rice

[a] Population figures are from the recently published census report for 1998 (Population Census Organization 2001). Please note that these figures are different from the ones used in a previous publication (van der Hoek 2001).

all the positive and negative impacts could one arrive at an informed decision on possibilities to maximize economic benefits and minimize health risks in the absence of resources for wastewater treatment.

It is in this light that the International Water Management Institute (IWMI) undertook studies in the Punjab, Pakistan. The present report is a synthesis of studies on wastewater-irrigation management, agricultural practices, economic costs and benefits, and environmental and health impacts in Haroonabad in the southern Punjab. More detailed separate reports are in preparation on these topics and on additional topics such as the role of wastewater irrigation in providing breeding habitats for mosquitoes.

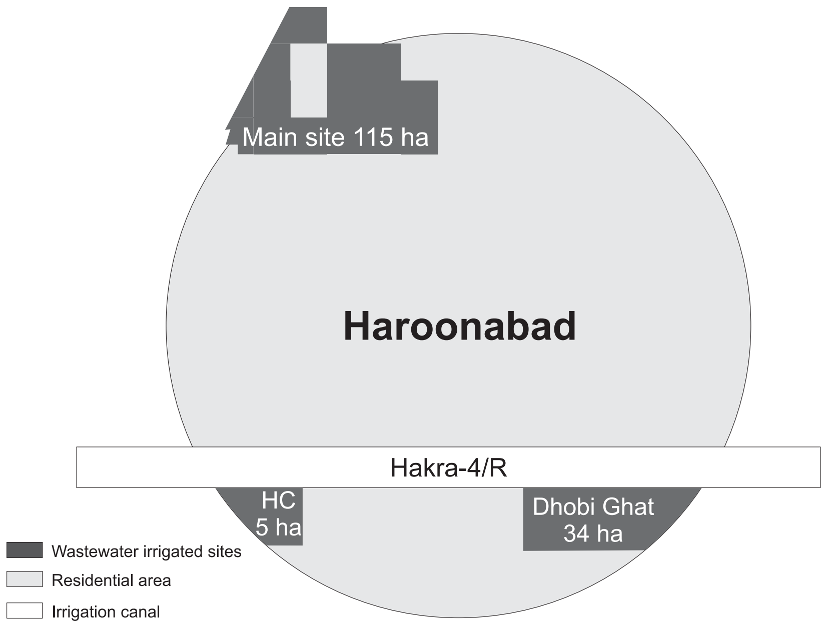
Study Area

Haroonabad is a town with 63,000 inhabitants (Population Census Organization 2001) located in the southern Punjab on the edge of the Cholistan Desert. There are no major industries in the town. The area has very limited natural water resources, and an extreme climate, with temperatures ranging from 2 °C in January to 48 °C in July, and with a average annual rainfall of 156 mm. As the groundwater is brackish the town depends on the Hakra-4/R irrigation canal for its supply of water.

Shortly after the construction of a sewage disposal scheme in 1965, farmers started using untreated urban wastewater around the disposal station. At present there are three pumps with capacities ranging from 50 liters per second to 70 liters per second at different sites that supply wastewater to agricultural fields (figure 1).

The municipal committee of Haroonabad town is responsible for the provision of a supply of water and waste disposal services to its citizens.

FIGURE 1.
Simplified schematic map of Haroonabad with the three sites irrigated with wastewater.



The municipality employs sanitary inspectors who have a crew of sewerage workers, sweepers, and pump operators with them to manage the tasks. The municipality auctions rights of wastewater use to the highest bidder regardless of the ownership of land. A group of lessees and landowners have been buying the wastewater as a single group to keep the prices of water low. Since they submit a single bid to the municipality, they operate as a monopolistic buyer. The usual amount was about Rs 140,000 per year (US$2,500). However, in 2000, the farmers refused to quote a price for the bid hoping to obtain it free of any cost, since the municipality had to dispose of the wastewater regardless of the value of the bid. In further negotiations with the municipal committee the farmers eventually agreed to pay a nominal amount of Rs 200 per hectare to cover the electricity bill of the wastewater pumps, as the municipality showed inability to finance the operation of the electric pumps.

The municipality's responsibilities end at the disposal station, from where the farmers take over the management of wastewater. The municipality is not responsible for the conveyance of wastewater to farmers' fields, and therefore, only farmers whose lands are located in the vicinity of the disposal stations are able to irrigate their fields. Over the years, the farmers have evolved mechanisms of cooperating with each other, and have converted an old irrigation channel into a wastewater channel. All wastewater-irrigating farmers have water rights for regular canal water, but they either sell it somewhere upstream or use it to irrigate their own fields located upstream.

In general, the richer landowners do not engage in direct farm operations for reasons of prestige, especially when wastewater is the source of irrigation. Instead, the landowners lease out their land for periods of several years. The lessees prefer to operate larger consolidated holdings by arranging leases with more than one landowner. The lessees generally assume the role of farm manager while the actual cultivation is done by the tenants on a sharecropping basis.

The water rights are automatically transferred with land, but the day-to-day distribution of water among various tenants takes place with their mutual cooperation and understanding. The farmers share water and its cost in proportion to the size of their land. They have devised a weekly irrigation roster specifying the duration of irrigation for each farmer depending on the size of the landholding, nature of the soil, and topography. This schedule is modified at an annual meeting, when farmers agree on their water and cost-sharing arrangements for the forthcoming year and devise a strategy for bidding for water.

Methodology

Agroeconomic Analysis

Information on wastewater use, payments for wastewater, changes in cropping pattern over time, and reasons for growing specific crops in wastewater-irrigated fields was obtained from interviews with key informants of various government agencies and by having group discussions and semi-structured interviews with farmers.

In order to assess the costs and benefits of wastewater agriculture to farmers, a representative sample of 40 farms was studied in detail. Half of the sample farms used wastewater as their source of irrigation and the other half used canal water and occasionally groundwater. All the sample farms were selected in such a way that they were located within a radius of 5 kilometers from the vegetable market in Haroonabad, so as to represent similar market opportunities. The data were collected over a one-year period from April 2000 to March 2001. All selected farmers grew vegetables commercially and were willing to share data about their incomes and expenses.

The selected farmers were interviewed every week using pre-designed and pre-tested questionnaires to collect information about the areas under different crops, sufficiency of irrigation water, cost of farm inputs such as seeds, fertilizer and pesticides, farming practices, crop yields, and the prices received for crop produce.

The production data on vegetables was difficult to obtain by interviewing farmers, as the farmers would only report the number of baskets sold on a specific day. In order to convert the baskets into weights, a random selection of baskets was weighed to standardize weight per basket for different crops. The data about vegetable prices were collected from the market committee, which is responsible for keeping a record of daily prices of vegetables and fruits traded at the market in Haroonabad.

Water and Nutrient Use

The methods used to estimate the efficiency of irrigation water and nutrient use are described in detail elsewhere (Ensink et al. 2002). Briefly, two wastewater use sites were considered: the main site of 115 hectares, which had been irrigated with wastewater for the last 35 years, and a smaller site of 34 hectares where wastewater irrigation started only 2 years ago (figure 1). A control site was included that was only irrigated with regular canal water from Hakra-4/R and had never received wastewater. At the three sites, a total of nine fields were selected to monitor irrigation and nutrient applications. Crops grown in the fields were cotton, fodder and cauliflower.

During the period May to September 2000, water delivery to the nine fields was monitored and information on fertilizer use was collected. The discharge from the pumping stations to the main canal was monitored every hour for three 24-hour periods using a flow meter attached to the pumps. Irrigation application to the fields was estimated from a flume that was installed at the water entry point to the selected fields, and water depth was measured continuously while farmers were applying water. These estimates multiplied with the number of irrigation events gave the actual volume of irrigation water. Groundwater levels were monitored in 28 piezometers in different locations in the fields, just before irrigation and 24 hours after irrigation and on a bi-weekly basis.

Wastewater samples were taken every 2 hours over two 24-hour periods at the pumping station to measure total nitrogen, phosphorus, and potassium. Analyses of nutrient concentrations were done using a portable spectrophotometer (Hach DR/2010, USA). Fluctuations of the concentrations over a day were small and, therefore, the average concentrations were used for the loading estimation. Average irrigation application depth and the total number of irrigation events within a cropping season were used to calculate the total application of all three nutrients for a cropping season. In most of the cases, the farmer supplemented the nutrients in the wastewater with chemical fertilizer. The total application of nutrients was compared with recommended application levels of fertilizer.

Water and Soil Quality

In addition to nitrogen, phosphorus, and potassium, the irrigation water, groundwater, and soil were checked for heavy metals and microbiological parameters at the two wastewater-irrigated sites and at the third site that had never received wastewater. The nine selected fields were sampled for nitrates in groundwater and heavy metals in the soil. The wastewater itself was sampled during a 24-hour period. Twelve samples were collected from the main wastewater site, four samples from the smaller site and two samples from the Hakra-4/R irrigation canal. Samples were taken within close proximity of the pump installation.

Composite soil samples were taken from the selected fields at six different depths (0-5, 5-10, 10-15, 15-30, 30-60 and 60-90 cm). Three samples were taken at each depth and these were composed as one sample and put in to a plastic bag. The samples were air-dried, crushed and passed through a two-millimeter sieve. Water samples to be tested for heavy metals were filtered through Whatman Filter paper-1. After digestion, the soil and water samples were analyzed at the Central Hi-Tec Lab of the University of Agriculture, Faisalabad for eleven different heavy metals by a Hitachi Z-8200 atomic absorption spectrophotometer.

The potential health risk from pathogens in untreated wastewater was assessed by analyzing water samples from the Hakra-4/R canal, the main wastewater site and the wash water of vegetables obtained from the wastewater-irrigated fields. All samples were examined for helminth eggs, while the wastewater samples and several canal water samples from the 4/R canal were tested for *Escherichia coli* as an indicator of fecal contamination.

Helminth eggs were examined using the Parasep® Faecal Parasite concentrator (Intersep Company, UK). *Escherichia coli* in wastewater and canal water samples were examined using the membrane filtration method. The water was filtered with a 0.45 mm Millipore filter under a vacuum pressure of 10 cm Hg and incubated on a ColiBlue 24 (Hach Company, Colorado, USA) growth agar.

The colonies of *E. coli* were counted and the number of these bacteria per 100 ml water sample was calculated.

Evaluation of Health Impacts

A cross-sectional survey was done to estimate the prevalence of intestinal parasitic infections in the residential area that was located in the middle of the main wastewater-irrigated site (figure 1). For comparison, two peri-urban settlements were included that had no access to wastewater and used either regular canal water or groundwater for irrigation. The majority of houses were constructed with bricks and the roads were partly paved in all three settlements. Furthermore, all three settlements were connected to the municipal water supply scheme, which gave a relatively reliable supply of drinking water.

All the households in wastewater and control settlements were selected on the basis that at least one person had been farming regularly during the previous 6 months. The selected study population included only members from these households who worked in the fields at least once a week or who were below 12 years of age. In the wastewater settlements, 43 households were identified on the basis of the criteria outlined, but after receiving information about the study through house visits and a community meeting, only 39 households with a total of 204 members agreed to participate in the survey. In the case of the control settlements, all the 65 households with 339 individuals that met the criteria agreed to participate in the study.

Trained staff administered a questionnaire for the selected people in April 2000, which included questions about diarrhea, skin and nail diseases, typhoid fever, cholera and hepatitis. The prevalence of these diseases, which could potentially be spread by wastewater, was estimated from the results of the health questionnaire. For diarrhea a recall period of 2 weeks was used.

Stool samples were collected and examined for intestinal parasites in May and June 2000. Stool sample bottles were distributed with the identification number and name of the selected individuals in Urdu script. The family members were instructed on how to provide a sample. The bottles were collected the next morning. Fresh stool samples were microscopically examined after concentration with the Parasep® Faecal Parasite concentrator (Intersep Company, UK). If the stool samples showed positive results, all the people were treated for helminth and protozoan infections.

Results

Water Availability and Water Use

Rainfall did not occur during the one-year study period but a large majority (80%) of the wastewater-irrigating farmers considered irrigation water availability as sufficient to cultivate the crops they had planted. In contrast, more than two-thirds of canal irrigators (70%) felt that the water supply was insufficient. The availability of reliable supplies of water was the main reason that high-value and short-duration crops such as vegetables and fodder were grown intensively at the wastewater sites. In the wastewater farms, vegetables covered 83 percent of the cropped area against a mere 18 percent in the canal-water farms (table 2). The wastewater irrigators on average applied 1,516 cubic meters of water per hectare over the one-year study period as compared to the canal irrigators who used 942 cubic meters per hectare. The wastewater supply

TABLE 2.
Cropping pattern of 20 canal-water farms (total land area 84 ha) and 20 wastewater farms (22 ha) in Haroonabad over a one-year period (April 2000 to March 2001).

Crop	Canal-water farms		Wastewater farms	
	Hectares	%	Hectares	%
Cotton	50	33	-	-
Wheat	49	32	-	-
Sugarcane	9	6	-	-
Fodder	14	9	10	17
Vegetables	28	18	48	83
Others	3	2		
Gross cropped area	153	100	58	100

ran continuously throughout the year and farmers not only did have their own turns, but could also exchange turns with each other to make water availability more responsive to crop water requirements.

The canal-water farmers, on the other hand, had fixed weekly irrigation turns, which constrained the flexible use of water. They could only irrigate when they had their own irrigation turn, as water was in short supply. In addition, the canal was operated on a rotation basis and sometimes the farmers faced severe water shortage due to the closure of the canal, especially during the summer season where the crops wilted faster without adequate water. The farmers could not use much groundwater for supplementing canal supplies because it was expensive as well as of low quality due to its high salinity levels. Canal-water farmers, therefore, had to grow crops that were less sensitive to water stress like cotton and wheat, which however, span longer cultivation periods and leave no time to cultivate a third crop. As a result, the cropping intensity (gross cropped area/total land area) at the wastewater farms was much higher (264 %) than at the canal-water farms (182 %) (table 2). Furthermore, due to the erratic nature of the water supply, canal-water farmers intercropped vegetables into sugarcane or cotton fields so that even if the vegetable crop failed, they could still reap some of the main crop.

Economics of Wastewater Agriculture

The cost of irrigation water was higher for the canal-water irrigators than for the wastewater irrigators. This was mainly due to the high cost of pumping groundwater, which canal-water farmers needed as a supplementary measure to meet crop water requirements (table 3). Wastewater farmers in Haroonabad mainly cultivated vegetables, which required more frequent and intensive labor inputs than canal-water farm crops, like cotton and wheat. Furrows and beds had to be prepared, frequent weeding and hoeing was necessary, and also the picking of vegetables was more laborious than harvesting wheat, cotton, or sugarcane. The wastewater farmers, therefore, preferred to utilize their own family members, including women and children, for the requisite labor input than rely on hired labor. The family labor input by wastewater farmers was 221 man-days per year per hectare against the 86 for canal-water farmers. The wastewater farmers did not use hired labor but canal-water farms used on average 37 man-days of hired labor per year per hectare. The use of family labor saved the wastewater farmers roughly 50 percent of the gross margin of a canal-water-irrigated farm annually.

Overall, there was no significant difference in total cash costs of farm inputs between wastewater farms and canal-water farms (table 3). Wastewater farmers spent more on land preparation, seeds, and pesticides. On the other hand, they applied significantly lower doses of fertilizer and no farmyard manure at all. The canal-water farmers, however, used almost twice the amount of nitrogenous fertilizer as the wastewater farmers (290 kg/ha nitrogen against 152 kg/ha) and the difference in phosphorus application was even larger (91 kg/ha against 16 kg/ha). This difference in fertilizer requirements may have been influenced by the differing crop patterns of wastewater and canal-water farms. Although this difference in fertilizer application resulted in a lower cost of fertilizer for wastewater farmers (only one-third the cost of canal-water farmers) there was no significant difference in the total cost of either type of irrigation.

TABLE 3.
Comparison of financial costs of inputs and value of products for wastewater and canal-water-irrigated farms (with dissimilar cropping patterns). The numbers in the table are means that were compared with the *T* test.

Description of variable (unit)	Canal-water farms (n=20)	Wastewater farms (n=20)	*T* value
Annual cost of irrigation water (Rs/ha)	1,141[a]	200	3.66**
Annual water charges (Rs/ha)	385	678	2.62**
Cost of hired labor (Rs/ha)	2,940	0	
Cost of land preparation (Rs/ha)	2,897	4,734	4.54**
Cost of seeds (Rs/ha)	2,903	5,409	3.44**
Cost of chemical fertilizers (Rs/ha)	5,484	2,621	5.19**
Cost of farmyard manure (Rs/ha)	1,626	0	
Cost of pesticides (Rs/ha)	5,378	7,458	2.57**
Total cash costs of inputs (Rs/ha)	22,754	21,100	0.85
Land productivity: Gross value of product (Rs/ha)	57,183	68,118	1.89*
Gross margin (Rs/ha)	34,429	47,217	2.50**
Water productivity (Rs/m^3)[b]	61	45	
Returns to water (Rs/m^3)[c]	37	31	

[a]Average cost of pumped groundwater used to supplement canal water
[b]Gross value per volume of water
[c]Gross margin per volume of water
**Significant at 0.05 probability level
*Significant at 0.10 probability level
Rs/ha = rupees per hectare
Mid-year exchange rate for the year 2000 was US$1 = Rs 56

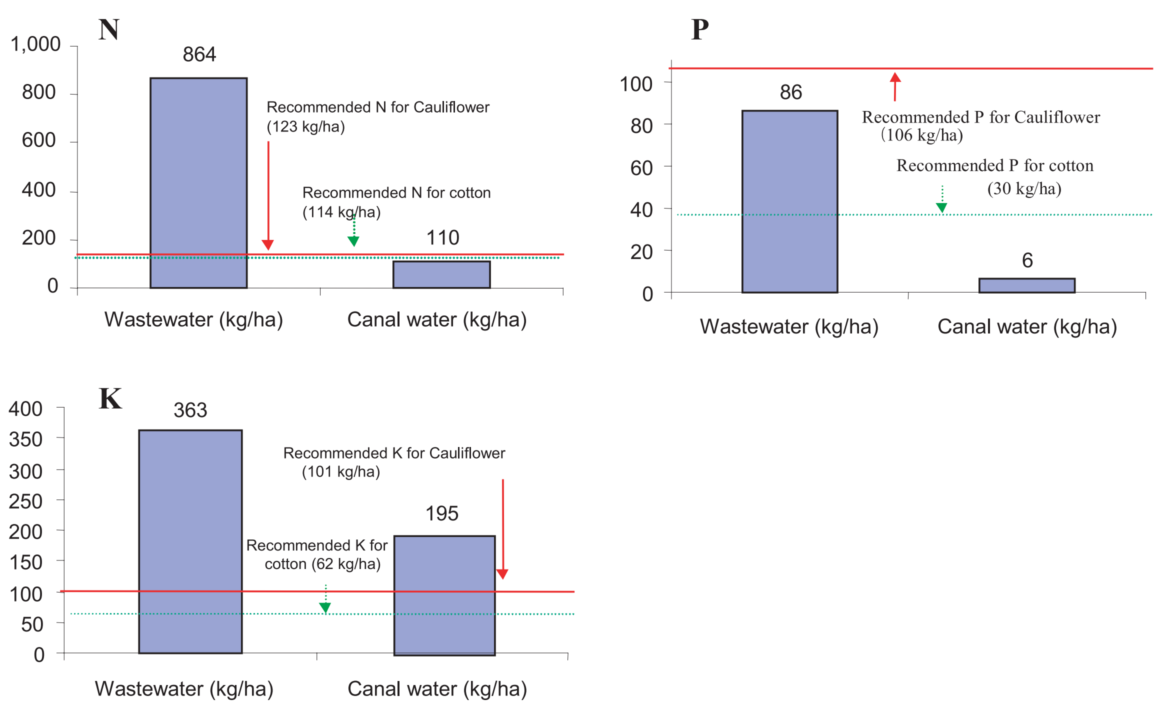
The detailed field study showed that except for phosphorus, nutrients were applied to wastewater-irrigated fields in excess of the recommended doses specified by the Ministry of Food, Agriculture and Livestock (1997) (see figure 2). The farmers did not report negative impacts as a result of excessive nitrogen application such as excessive growth and poor quality of crop products, but claimed that they had to use more pesticides due to weeds.

The major advantage of the wastewater farms was the high crop production. In addition, despite the perishable nature of vegetables and price cycles, their gross product value remained significantly higher than that of the canal-water farms. The gross margins (gross value of product minus gross cash costs) of wastewater farmers were also significantly higher than those of the canal-water farmers.

While the land productivity was significantly higher at the wastewater farms, this was not the case for the water productivity (table 3). Wastewater farmers had to over-irrigate, especially during the rainy season, when they had too much water.

It was not possible to compare the wastewater-irrigated fields with canal-water-irrigated fields that had a similar cropping pattern, because almost all wastewater farmers took advantage of reliable supplies of wastewater by growing vegetables that could not easily be grown by the farmers who had to rely on canal water. However, a comparison was made for cauliflower, which was grown by all the wastewater farmers and by three

FIGURE 2.
Comparison of seasonal nitrogen (N), phosphorus (P), and potassium (K) application by wastewater and canal-water irrigation. The two horizontal lines represent the amounts of N-P-K application recommended for cauliflower and cotton under-Pakistan conditions (Ministry of Food, Agriculture and Livestock 1997).



canal-water farmers. A comparison of the cost of production and the value of outputs of cauliflower highlighted differences in the production techniques of the crop between wastewater and canal-water areas.

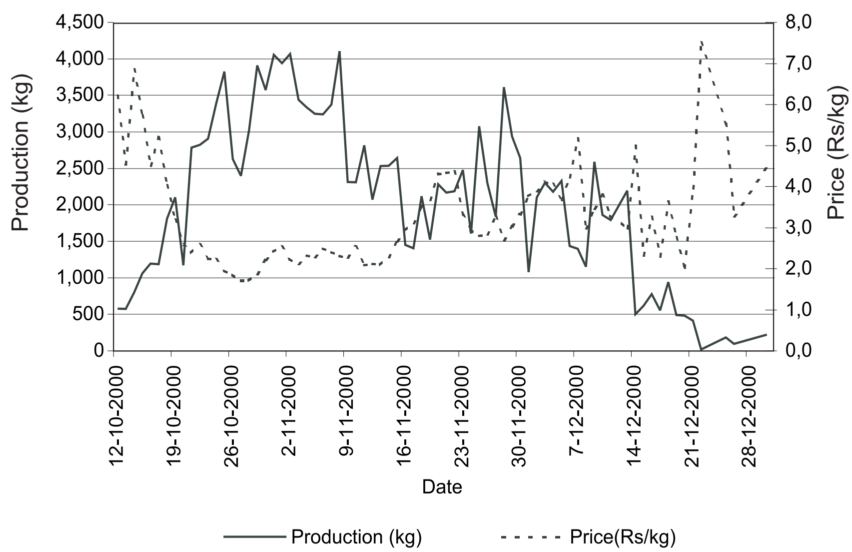
In wastewater-irrigated fields, the farmers used disc harrows to uproot the previous crop. This method cost much more than the ordinary method of cultivating and, therefore, the production cost of cauliflower was higher in wastewater farms than in canal-water farms (average Rs 3,354 versus Rs 2,023). The canal-water farmers, however, spent almost twice as much as wastewater farmers on fertilizer (Rs 5,008 versus Rs 2,420). The physical yields of cauliflower on the wastewater farms were higher than on canal-water farms (13,170 kg/ha versus 9,720 kg/ha). Due to the small number of canal-water farms that cultivated cauliflower no statistical comparisons were done.

In general, wastewater farmers did not cultivate root vegetables claiming that they had no access to clean water to wash vegetables. In addition, some root crops like radish, carrot and turnips were reported not to grow well in fields with continuous wastewater irrigation. Some crops showed more vegetative growth, thereby affecting fruit formation. Some other vegetables such as bottle gourd, okra, and beans were reported to be affected by high insect attacks. Wastewater farmers, therefore, had a limited number of crops to grow, such as spinach, chilies, pumpkins, eggplants, onions, tomatoes, cauliflower, and fodder.

Wastewater farmers in the area also faced market constraints. The marketable surplus of vegetables of individual farmers was too small to export to bigger markets. As a result, the farmers tended to sell their vegetables in the local market, where demand was rather limited and inelastic. With all farmers growing similar crops and marketing the produce during the same period in a rather limited market, there was an excess supply in the market during peak seasons, which resulted in a drop in prices and a decline in returns to the farmers.

Figure 3 depicts the variability of prices in relation to the change in production of cauliflower. In the beginning of the harvesting season supply was low and prices were high but as production approached its peak the prices fell to their

FIGURE 3.
Production and price cycle of cauliflower at the Haroonabad market for one cropping season. (Data were obtained from the Market Committee, Haroonabad.)



minimum. There was, therefore, a clear relationship between prices and production. Vegetables are perishable commodities having very short shelf life, thereby compelling farmers to sell all of their produce as soon as it is harvested.

While the prices of vegetables were determined solely on the basis of supply and demand forces, the government fixed procurement prices of wheat and cotton (which were the common crops in canal-water-irrigated areas) even before they were planted. These farmers, therefore, had a sufficient degree of certainty that they could sell their produce at the predetermined procurement price.

Irrigation Water Quality

Wastewater had levels of *E. coli* and worm eggs that clearly exceeded the international standards for irrigation and could, therefore, pose a potential risk to human health (table 4). Eggs of a wide variety of helminth species were detected in the water at the main wastewater disposal station, including hookworm, roundworm (*Ascaris lumbricoides*), whipworm (*Trichuris trichiura*), dwarf tapeworm (*Hymenolepsis nana*), and beef tapeworm (*Taenia saginata*). However, no worm eggs were detected in the wash water from vegetables grown on the wastewater-irrigated fields.

TABLE 4.
Quality of wastewater and canal water (Hakra-4/R canal) in Haroonabad in relation to internationally recommended quality standards.

Parameter	Unit	Wastewater	Hakra-4/R	Irrigation water quality standard[a]
E. coli	No./100 ml	6.3×10^7	1.6×10^3	1.0×10^3
Helminth eggs	No./l	100	N.D.	1
Total dissolved solids (TDS)	mg/l	2076	202	450
Electrical conductivity (EC)	dS/m	4.4	0.4	0.7
Sodium (Na)	mg/l	199.0	46.8	70.0
Sodium adsorption ratio	mg/l	4.5	1.0	3.0
Total Nitrogen (N)	mg/l	78.3	8.0	5.0
Total Phosphorus (P)	mg/l	8.6	0.2	-
Total Potassium (K)	mg/l	34.7	7.1	-
Manganese (Mn)	mg/l	0.07	0.12	0.20
Chromium (Cr)	mg/l	0.23	0.03	0.10
Lead (Pb)	mg/l	0.04	0.13	5.00
Nickel (Ni)	mg/l	0.14	0.17	0.20
Copper (Cu)	mg/l	0.35	0.12	0.20
Cobalt (Co)	mg/l	0.06	0.09	0.05
Cadmium (Cd)	mg/l	0.01	0.02	0.01
Iron (Fe)	mg/l	0.22	0.01	5.00
Zinc (Zn)	mg/l	N.D.	0.10	2.00

[a]Standards for *E. coli* and helminth eggs as recommended by WHO (WHO 1989). Other standards as recommended by FAO (Pescod 1992).
N.D. = not detected with the method used.

Traditionally, irrigation water is grouped into various quality classes that provide a rough indication of potential adverse effects on crop growth. Important parameters for crop growth are salinity, as measured by electrical conductivity (EC), total dissolved solids (TDS), and the sodium adsorption ratio (SAR). According to FAO guidelines (Pescod 1992), TDS as well as EC would place the wastewater in Haroonabad in the "severe" restriction on use group, while the restriction on use based on the measured SAR would be "slight to moderate." The levels of sodium in the wastewater could well lead to accumulation in plants and direct toxicity resulting in a reduced yield. It was remarkable that despite the high TDS and salt levels, farmers during the course of the study did not complain about negative effects on vegetable yields.

While nutrients such as nitrogen, phosphorus, and potassium are beneficial to plants, the level of nitrogen in the wastewater was too high and could lead to excessive vegetative growth. The degree of restriction for irrigation would be "severe" for wastewater but the canal water, which also had high nutrient content, would be in the "slight to moderate" degree of restriction for use group.

The high nutrient and *E. coli* counts in Hakra-4/R water could have been due to the unchecked entry of hundreds of cattle and buffalo for bathing and drinking in the canal each day.

All the heavy metals tested fell within the standards set by the Pakistani government for wastewater disposal and the FAO standards for irrigation (Pescod 1992). Only chromium and cobalt concentrations could pose a (minimal) risk to crop growth based on the maximum permissible guideline concentrations.

Groundwater Quality

Groundwater in the entire study area was brackish and, therefore, was not used for drinking or other domestic purposes. However, it was clear with the high levels of salinity, fecal contamination, and nitrate observed in the groundwater immediately below wastewater-irrigated fields that wastewater irrigation had further deteriorated the groundwater quality compared to non-wastewater-irrigated fields (table 5). Groundwater depth was on average 1.46 meters from the surface and was quite stable over the monitoring period (coefficient of variation 14.4%).

Heavy Metals in Soil

The heavy metal concentration levels that were found in the soils of the wastewater-irrigated fields were unlikely to affect crop production as they were within the range of normal soil concentrations (Page and Chang 1985). The main site had been irrigated with wastewater for 35 years, the minor site for 2 years, and the control site had always been irrigated with regular canal water. There appeared to be a trend towards the accumulation of lead and copper in the long-term in wastewater-irrigated fields (table 6). Heavy metals applied to field soils would be expected to accumulate mainly near the surface. The fact that no differences were found in heavy metal

TABLE 5.
Groundwater quality below agricultural fields in Haroonabad irrigated with and without wastewater.

Parameter	Unit	Non-wastewater irrigated	Wastewater irrigated
Electrical conductivity (EC)	dS/m	2.8	5.4
E. coli	No./100 ml	20	338
Nitrate (NO_3)	mg/l	47.0	67.9

TABLE 6.
Average soil heavy metal concentrations in mg/kg at three sites in Haroonabad.

	Main site	Minor site	Control site
Lead	10.8	5.3	0
Nickel	28.4	22.5	27.8
Cobalt	12.4	11.2	6.8
Copper	64.1	21.9	9.6
Manganese	242.7	185.7	183.1
Chromium	51.7	64.2	98.1

concentrations between the upper (0-5 cm) and lower (60-90 cm) depths makes it unlikely that the wastewater had contributed significantly to the heavy metal concentrations. Sources of the lead and copper have not been identified, but the high concentration of copper could be due to aged copper pipes in the water supply system of the town, while the increased levels of lead could be associated with exhaust fumes from the buses at the station situated next to the main wastewater-irrigated site.

Human Health Impacts

The health questionnaire was filled by 99.5 percent of the exposed and 97.1 percent of the unexposed study population. The number of people willing to provide a stool sample was lower with a coverage of 66.2 percent in the exposed population and 55.5 percent in the unexposed population, though this group was still representative of the entire selected population.

Members from families that were irrigating their land with untreated urban wastewater around Haroonabad had a significantly higher occurrence of diarrheal diseases than those who irrigated their land with canal or tube-well water (table 7). The group exposed to wastewater reported more nail problems than those in the control group, but not to a degree of statistical significance. Nail problems were most frequently observed in male adult farmers, and the most common nail problem was koilonychia (spoon formed nails), which is associated with iron deficiency anemia. The only problems frequently mentioned in open questions on health were fever and colds, which therefore, appear as such in table 7.

The prevalence of hookworm and roundworm (*Ascaris lumbricoides*) infections was higher in the population exposed to wastewater than in the control group (table 8). The prevalence of hookworm among adult, male wastewater-farm workers was 80 percent, which is an extremely high figure for Pakistan. In children, however, there was no significant difference between the exposed group and the unexposed group. More details are provided in Feenstra et al. (2000a).

TABLE 7.
Prevalence of self-reported diseases by exposure to wastewater.

Disease	Exposed n = 203	Unexposed n = 329	χ^2	*p* value
Diarrhea	(24) 11.8%	(18) 5.5%	6.96	0.008
Skin problems	(6) 3.0%	(16) 4.9%	1.15	0.283
Nail problems	(16) 7.9%	(14) 4.3%	3.10	0.078
Fever/cold	(24) 11.8%	(39) 11.9%	0.01	0.991

TABLE 8.
Prevalence of intestinal parasitic infections by exposure to wastewater.

Disease	Exposed n = 135		Unexposed n = 188		χ^2	*p* value
Giardia lamblia	(48)	35.6%	(64)	34.0%	0.08	0.778
Entamoeba coli	(51)	37.8%	(84)	44.7%	1.54	0.215
Entamoeba histolytica	(20)	14.8%	(17)	9.0%	2.58	0.108
Ascaris lumbricoides	(7)	5.2%	(0)	0.0%	9.96	0.002
Trichuris trichiura	(1)	0.7%	(0)	0.0%	1.40	0.237
Hookworm	(53)	39.3%	(52)	27.7%	4.82	0.028
Taenia saginata	(1)	0.7%	(0)	0.0%	1.40	0.237
Hymenolepis nana	(12)	8.9%	(26)	13.8%	1.85	0.174

Discussion

The results from this study highlight the economic value of untreated urban wastewater in Pakistan. The most important benefit to farmers in this semi-arid country is the reliable supply of wastewater, which allows them to grow high-value vegetable crops. The wastewater supply runs continuously throughout the year and farmers not only have their own turns in using it, but can also exchange turns with each other to make water availability more responsive to crop water requirements. The canal-water farmers, on the other hand, have fixed, weekly irrigation turns, which constrains the flexible use of water. The water supply in canal-water farms is also disproportionate to the amount required. In addition, the canals are operated on a rotation basis and sometimes the farmers faced severe shortage due to canal closure, especially since groundwater could only be used to a limited extent because of its prohibitive cost and high salt levels. Cheema et al. (1997) reported that along the Hakra-4/R canal, 40 percent of the farmers missed 10 or more irrigation turns in a year. Since the high-value crops grown here require a reliable water supply, wastewater farmers have a distinct monetary advantage.

The wastewater farmers also made significant savings on chemical fertilizer and manure, irrigation water, and hired labor. However, they had to spend significantly more on agricultural operations, seeds, and insecticides. Despite the market-related disadvantages to wastewater farmers, the gross value of product and the gross margins at the wastewater farms were significantly higher than those of the canal-water-irrigated farms.

The use of wastewater for irrigation in this area has almost no opportunity cost, as a supply cannot be redirected to another use, area or farmer if it is in excess of one's needs. Farmers, therefore, tend to over-apply wastewater, as they have to “consume” the entire irrigation turn within their own area. Canal water, on the other hand, is rather erratic due to water shortage and scarcity, and farmers use groundwater as a supplemental source of water only when the crop is about to wilt. This results in an increase in overall water productivity for canal water irrigation. Additionally, the returns to water (gross margin per volume of water) are slightly higher for the canal-water farms, indicating a potential for improved profits per unit of water at wastewater farms if the farmers use less wastewater, or use the same water over a larger area.

The value of wastewater was reflected in the land rents, which on average were 3.5 times higher for wastewater fields than for canal-water fields. Higher land rents for wastewater farms on average result in higher income for the landowners but relatively less net profit for lessees. A proper economic analysis would have included all benefits and costs, including, for example, the opportunity costs of family labor, and environmental, health, and social impacts (Hussain et al. 2001).

Children under 15 years of age provided important labor inputs at the wastewater farms. However, school enrolment of the children of tenants in this area is generally low, irrespective of whether the tenant is cultivating on wastewater or canal-water-irrigated lands. School enrollment seems to be more dependent on the general socioeconomic status of the family than on the specific labor requirements associated with the type of cultivation. Picking vegetables and cotton are mostly female occupations by tradition. Wastewater-vegetable farming, therefore, offers employment opportunities for women, which are otherwise rather scarce in small towns of Pakistan, like Haroonabad.

The excessive water and nutrients use by wastewater farmers suggests that with a more rational use, more farmers could benefit. This would be feasible from an engineering point of view. However, additional wastewater conveyance infrastructure cannot be built until all adjoining farmers agree to let the water channel pass through their lands. Earlier experiences in collective action at the tertiary level of the irrigation system in Pakistan suggest that it is extremely hard for farmers to cooperate in building and sharing new infrastructure unless the channel is a state property[1] (Mirza and Merry 1979; Mirza 1975; Merry 1986; Malik et al. 1996).

When municipalities plan and implement wastewater schemes, they need to involve the potential wastewater users in the design of the schemes, especially the watercourses and drainage channels, through well-structured social mobilization processes and methodologies. Such approaches will facilitate a more efficient, equitable, and environmental-friendly use of wastewater for agriculture, thereby maximizing private economic benefits for larger numbers of farmers and reducing negative environmental impacts caused by the excessive application of nutrients and water.

Against the obvious direct economic benefits of wastewater use, there are important negative impacts on human health. This study provided evidence of an increased risk of hookworm infection among male wastewater farmers. Overall, the prevalence of helminth infections in this peri-urban area was much higher than in a nearby group of 10 rural villages (Feenstra et al. 2000b).

Both diarrheal diseases and nail problems were more common in farmers exposed to wastewater than those exposed to canal water. The high prevalence of koilonychia (spoon shaped nails) can be explained by the very high occurrence of hookworm infections observed in male farm workers exposed to wastewater. Hookworm infections can cause anemia by blood loss due to damage of the intestinal wall. Hookworm infections occur when larvae, that are

[1]Most of the tertiary irrigation channels of the canal network are state channels (*Sarkari Khal*) in the Punjab Province, to which farmers connect their private channels to irrigate. Due to this very reason, a number of water-related disputes in irrigation communities refer to the route of the channel, diversion points from where farmers get water, and water allocations.

present in the soil, penetrate through the skin of farmers when they are working barefoot in wastewater-irrigated fields. The prevalence of hookworm infections was not significantly different, however, between children of exposed and unexposed farmers. Other studies have shown significant excess infection with intestinal helminths in wastewater-farm workers, while there is to date no convincing evidence that wastewater workers are at higher risk of protozoan, bacterial, and viral infections (for a recent review, see Blumenthal et al. 2000).

Moreover, farmers, their families, and crop consumers might also be at risk, because the vegetables grown in the wastewater-irrigated fields are eaten uncooked. For instance, tomatoes, which are a major crop grown in the wastewater-irrigated fields, are widely used uncooked in salads. Helminth eggs and bacteria present in wastewater can contaminate these vegetables and pose a health risk to consumers (WHO 1989; Blumenthal et al. 1996). We found no worm eggs in the wash water from vegetables that were grown in wastewater-irrigated fields. This could be due to the bed and furrow practice of cultivating vegetables, in which the vegetables do not come in to direct contact with the wastewater. This cultivation method, therefore, seems to be appropriate to the local conditions.

It is clear that these important human health issues have to be addressed in order to make wastewater use sustainable. To avoid health risks, standards were recommended by international organizations, but the scientific basis for these standards is still weak (Shuval 1991). It has even been suggested that the numerical values of fecal coliforms that are used in water quality standards are based on philosophy and experience rather than on science (Cooper 1991). More realistic policies and guidelines for wastewater use are, therefore, needed.

Wastewater irrigation in Haroonabad had clearly deteriorated the quality of groundwater. The observed fecal contamination and nitrate concentration could pose a risk to human health if the water was to be used for drinking (WHO 1989). However, this is hypothetical in the study area given that the groundwater is unpalatable because of its high salt content.

Levels of heavy metals in water and soils were low, which is not surprising in this small town without major industries. It is believed that levels of heavy metals in irrigation water are likely to be toxic to plants even if at concentrations below that at which they pose a significant risk to human health (Cornish et al. 1999). An ongoing study in Faisalabad, an industrial town of more than two million people, should show whether our conclusions from the limited case study in Haroonabad are applicable elsewhere under different conditions.

Although the disposal of wastewater on agricultural fields has many benefits, the use of this water without any treatment poses serious health risks to farmers and their children. Protective measures are, therefore, required for farmers, their families and crop consumers. If treatment of the water is not possible because of high costs, other protective measures should be taken. Low-cost interventions could include information on hygienic behavior for farmers, such as wearing of shoes and gloves while working in wastewater-irrigated fields, regular treatment of farmers and their families with antihelminthic drugs and crop restrictions in wastewater-irrigated fields.

One issue, which has not been addressed in international guidelines and in the literature on health impacts of wastewater use, is the fact that many people depend on untreated surface water as a supply of drinking water (van der Hoek et al. 2001). If untreated urban wastewater is disposed of in the canal system instead of being used, it would pollute the drinking water supplies of people downstream. The use of wastewater instead of disposal could, therefore, provide health benefits for communities located downstream of the town, which depend on surface water sources for their supply of domestic water. At this stage this is largely speculative, as the actual health risks of the disposal of urban wastewater in surface water for domestic users downstream, are unknown.

An ongoing study of IWMI in Pakistan attempts to model the water quality in an irrigation canal system in order to quantify the aforementioned risk under different scenarios of wastewater use and disposal. In all existing guidelines, the focus is on health risks for the wastewater farmers, the communities around the wastewater-irrigated fields and the consumers of the produce from the fields rather than communities located downstream.

We argue that in situations such as Pakistan, a different approach should be followed, in which both the potential positive and negative health impacts of wastewater irrigation for affected parties are considered. In this approach, wastewater management is seen within the framework of integrated resource management at river basin level. Water quality problems should also be addressed at the river basin level. The integration of wastewater management and pollution control interventions and policies within the broader water resources management policies are essential for achieving the efficient use of the scarce resources available and would allow for an assessment of negative and positive health impacts of wastewater use.

Conclusions

In cities like Haroonabad where water is scarce, poor farmers use untreated wastewater. And, as industrial pollution is limited, there is scope for improvement in the use of water and nutrients to further optimize the economic benefits of wastewater use. Wastewater farmers have an abundance of water and nutrients and, therefore, apply them in excessive amounts. A different distribution system, however, could provide benefits to more farmers and thereby contribute to increased agricultural production and poverty reduction. Such a change in system entails adaptations in both physical infrastructure as well as management.

At the same time adequate measures should be put in place to control worm infections in populations exposed to wastewater. While treatment of wastewater before use would reduce health risks, this is not a realistic option in many resource-deficient cities. The communities of wastewater farmers in small towns such as Haroonabad are small, localized, and rather homogenous. These are good conditions in which to introduce effective health protection measures that should include health education, and regular antihelminthic medication of exposed people. The commonly used drugs against soil-transmitted helmiths are safe and effective and, as such, regular de-worming campaigns are likely to have an important impact on the health status of people exposed to untreated wastewater.

Using untreated urban wastewater is undesirable and even unacceptable to many, but it is a reality for many poor farmers who are unlikely to benefit from wastewater treatment facilities any time soon. The Haroonabad case study suggests that it is possible to further increase benefits of urban wastewater in small towns even when treatment is not a feasible option. Such an endeavor requires a new look at wastewater irrigation practices and entails the need to devise realistic methods for maximizing benefits and reducing risks under the prevailing social and economic conditions.

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