RESEARCH
REPORT

64

Use of Untreated Wastewater in Peri-Urban Agriculture in Pakistan: Risks and Opportunities

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International Water Management Institute

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Contents

Summary

The practice of using untreated wastewater for irrigation is widespread but has been largely ignored because the norm has always been that wastewater should be treated before use. Increasing water scarcity, lack of money for treatment and a clear willingness by farmers to use untreated wastewater have led to an uncontrolled expansion of wastewater use. It is therefore important to better document the practice of irrigation with untreated wastewater in order to find out how it could be improved within the financial possibilities of very low-income countries.

The town of Haroonabad in Pakistan's arid southern Punjab was selected for a case study on the costs and benefits of the use of untreated wastewater for irrigation. The study looked at health, environment and socioeconomic aspects of irrigation with untreated wastewater. This report deals with the environmental aspects of the study. The objectives of the study were:

- To identify the environmental impacts of wastewater use in a small town in Pakistan.
- To estimate water and nutrient application efficiencies and suggest ways to make better use of wastewater as a resource.

As expected, the wastewater in Haroonabad contained high numbers of fecal coliform bacteria and worm eggs, and was therefore not fit for unrestricted irrigation according to international standards. However, the regular canal irrigation water also failed to meet the quality standards and this raised the question whether current guidelines are appropriate for a country like Pakistan. The application of nitrogen, phosphorus, and potassium through wastewater exceeded agronomic recommendations for the crops being cultivated.

Wastewater is a highly valued resource by farmers in Pakistan and other countries. In the case of Haroonabad it was clear that improved water and nutrient fractions through conjunctive use of fresh irrigation water and wastewater, on a three to one ratio, would make the benefits of wastewater available to a larger group of farmers, and would at the same time reduce negative environmental and public health impacts.

Heavy metal buildup in soil was not significant and it is unlikely that heavy metals are an important factor in small cities without major industries. Groundwater contamination is often considered to be an important negative impact of wastewater use. However, when the natural groundwater in an area is saline and unfit for use as drinking water, this is of minor concern. The only alternative to the direct use of wastewater for irrigation was to dispose of it in a nearby irrigation canal. However canal water in many parts of Pakistan is used further downstream as a drinking water source. Thus, by using untreated wastewater for properly managed irrigation, health risks remain known and localized.

In low-income countries with insufficient resources for investment in wastewater treatment and a lack of capacity to enforce legislation, untreated wastewater is used wherever this is attractive to farmers. The reality is that farmers will take health risks and continue to use wastewater when there is an opportunity for direct economic benefits to themselves. This is more evident in cases where there is a lack of access to other sources of irrigation water. Therefore, rather than concluding that treatment facilities should be provided or strict legislation enforced, we suggest that there is a need to take a new look at wastewater irrigation, and come up with realistic options for maximizing the benefits and reducing the risks under a particular set of given social and economic conditions.

Use of Untreated Wastewater in Peri-Urban Agriculture in Pakistan: Risks and Opportunities

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Introduction

Urban Wastewater Use in Agriculture

Many countries worldwide are entering a period of severe water shortage. Increasing competition for water among urban centers, industry and irrigated agriculture together with rapidly growing populations will put current agricultural and irrigation practices under severe pressure because irrigation is by far the largest user of water.

In 2015, it is expected that for the first time, the majority of the world's population will be living in urban areas (UNPD 1998). This will be particularly evident in the south. By 2050 an estimated 80-percent of the world's population, 7.3 to 10.7 billion (UNPF 1999) will be living in developing countries, of whom over 55 percent will be living in cities. This rapid urbanization has led to a deterioration of living conditions within cities, especially in the peri-urban areas. Investments in drinking water supply, sanitation, wastewater disposal and treatment facilities have not followed the pace of urbanization. As a result rivers, lakes and other freshwater bodies close to cities are polluted and downstream communities are forced to use unsafe water or treat the water at high cost. If wastewater is disposed of as currently recommended, a water source high in nutrients is lost to urban and peri-urban agriculture at a time when this type of agriculture is seen by many as one of the solutions for food scarcity and unemployment, offering a livelihood to many of the urban poor (SIUPA 2000).

While wastewater use in agriculture has been taking place for decades, and even centuries, in countries like Mexico, Vietnam and China (Shuval et al. 1986), it is now receiving renewed recognition as a potential water source under conditions of increased freshwater scarcity. In Saudi-Arabia, Jordan, India, Pakistan and Israel the use of wastewater is now a common practice. Israel is one of the leading countries in wastewater usage as it expects that 70 percent of its agricultural water demand in 2040 will be met by treated wastewater (Haruvy 1997).

With three major crop nutrients present in wastewater it seems evident that wastewater will benefit crop production. Several studies have shown the positive impact that wastewater has on crop production (Khouri, Kalbermatten and Bartone 1994; Scott, Zarazqa and Levine 2000). Wastewater, especially if it contains industrial effluent, can contain levels of nutrients, metals and other constitutes that are toxic for plant growth. Nitrogen, for example, although essential for growth and reproduction will, in cases of over application, lead to a prolonged vegetative stage, making the crop more susceptible to pests and diseases eventually resulting in lower yields (Morishita 1988). Water quality, together with climatic conditions, physical and chemical soil properties, and water management practices to a large extent determine the maximum crop yield. The quality of water becomes increasingly important in semi-arid and arid climates as high evaporation could lead to the accumulation of different compounds present in wastewater.

Concern for public health has been the most important constraint in the use of wastewater. Wastewater carries a wide spectrum of pathogenic organisms posing a risk to agricultural workers, crop handlers and consumers (Blumenthal et al. 2001; Shuval et al. 1989). High levels of nitrogen in wastewater may result in nitrate pollution of groundwater sources used for drinking, which could lead to adverse health effects. Accumulation of heavy metals in soils and its uptake by plants is another risk associated with wastewater irrigation (Khouri, Kalbermatten and Bartone 1994).

On the other hand, wastewater is seen as a reliable water source, and crops are produced close to consumer markets so that perishable high-valued crops like vegetables can be grown. Because of the high levels of essential macronutrients—nitrogen, phosphorus and potassium—in wastewater, the additional application of chemical fertilizers becomes unnecessary, or can be considerably reduced. These nutrients make wastewater a valued water source for farmers who are willing to pay a higher fee for wastewater than for regular irrigation water.

Guideline values set by the World Health Organization (WHO) and United Nations Environment Program (UNEP) place restrictions on crops grown with wastewater and advise at least some sort of treatment before its use (Mara and Cairncross 1989; Blumenthal et al. 2000). Excellent treatment options exist that can remove all harmful pathogens and bring heavy metal and nutrient loads within safe limits for use or disposal. However, due to lack of funds for treatment and control, planned and regulated use of wastewater remains, for many developing countries, an unobtainable goal in the near future. Most municipalities have only two options for wastewater: disposal in open water bodies or turn a blind eye to its use for agricultural purposes.

In using wastewater for irrigation, the direct (actual contact with wastewater) health risks are localized within an irrigated area and the exposed group is relatively small. Larger populations of downstream water users will be exposed to uncertain health risks if wastewater is dumped in open water bodies. This applies especially in semi-arid and arid countries where the only open water bodies are irrigation canals and agricultural drains. These irrigation canals serve multiple uses for households besides agriculture, such as washing, bathing and even drinking (Yoder 1981; van der Hoek et al. 2001).

A small survey conducted by IWMI in twelve towns and cities in southern Punjab, Pakistan revealed that in all cities where wastewater disposal schemes were present, wastewater irrigation occurred around the disposal stations. Wastewater was used in all cases without treatment and without restriction on type of crop grown. The predominant crop type was vegetables, including root crops like carrot and potato. In some instances a fee was paid to the authority in charge of disposal of wastewater for its use. In all cases, the responsible authorities were aware of this practice and, although they did not endorse it, they took no action to prevent it. The general attitude towards wastewater irrigation seemed to be that “the farmer knows best.”

The practice of using untreated wastewater for irrigation has hardly been studied because treatment has always been considered the only suitable option. In the light of increased water scarcity, lack of money for treatment and a clear willingness by farmers in some places to use untreated wastewater, studies that look into these practices and could recommend management options other than wastewater treatment are needed.

Pakistan Case Study

In the town of Haroonabad, untreated urban wastewater has been used for irrigation for the past 35 years. In February 2000, IWMI initiated an interdisciplinary study in this town focusing on health, environment and socio-economic aspects of irrigation with untreated wastewater. The results of the health component, presented in Feenstra, Hussain and van der Hoek (2000), showed a higher prevalence of hookworm infections in wastewater farm workers, who worked manually and barefoot in their fields compared to a similar unexposed group. The results of the socioeconomic component of the study showed a considerably higher income for wastewater farmers (van der Hoek et al. 2002). This report presents the environmental aspects of the study. The objectives were:

- To understand wastewater irrigation practices and their characteristics in an urban setting without major industry in order to identify the negative environmental impacts of current practices.
- To estimate water and nutrient application efficiencies and recommend ways to improve current practices.

Description of Study Area

Background

The town of Haroonabad (29° 37’ N and 73° 08’ E) is part of the Bahawalpur division in southern Punjab and is located on the edge of the Cholistan desert, close to the Indian border. The arid climate, with an annual average rainfall of 160 mm and potential evaporation of 2,500 mm a year, and temperatures ranging from 0° C in January to 48° C in July, makes agriculture without irrigation virtually impossible. Brackish groundwater, unfit for drinking and agriculture, makes the town dependent on the irrigation distributary canal, Hakra-4/R, for all water uses. In 1998 the population was 63,000 (Population Census Organization 2001) and apart from the seasonal cotton related industry—washing and ginning—there is no major industry in the town. Shortly after the construction of a sewerage system in 1965, farmers started using the untreated wastewater pumped from the newly constructed disposal station for irrigation. After the collapse of the sewerage system in 1979, due to heavy monsoon rain, several pumps were installed in and around the town to dispose the blocked wastewater, which led to the development of more wastewater-irrigated sites (figure 1).

Wastewater Irrigation Practices

A survey before the start of the study revealed that the number of irrigation turns with wastewater decreased with increasing distance from the pump (figure 2) at the main disposal station site. Approximately 50 percent of the 115 hectare site used only wastewater while the other half used both Hakra-4/R water and wastewater.

The wastewater irrigation practices were similar to those practiced in fields irrigated by Hakra-4/R water, which controlled flooding of bunded basins. Beds and furrows were used for vegetable cultivation. The average size of a wastewater farm and a Hakra-4/R irrigated farm was 1.1 hectares and 4.2 hectares, respectively.

FIGURE 1.
Location of wastewater irrigated areas near the town of Haroonabad (not to scale).

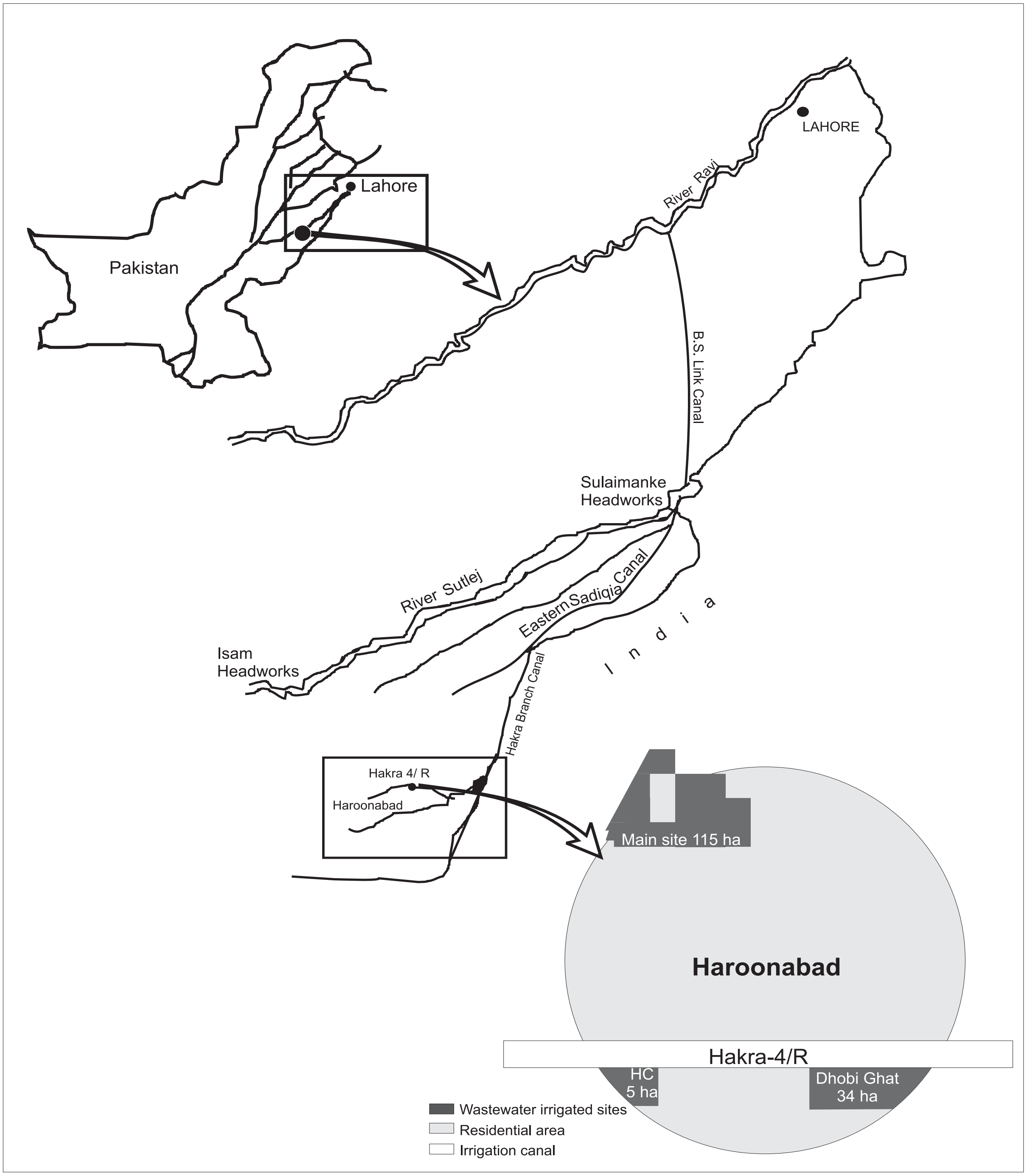
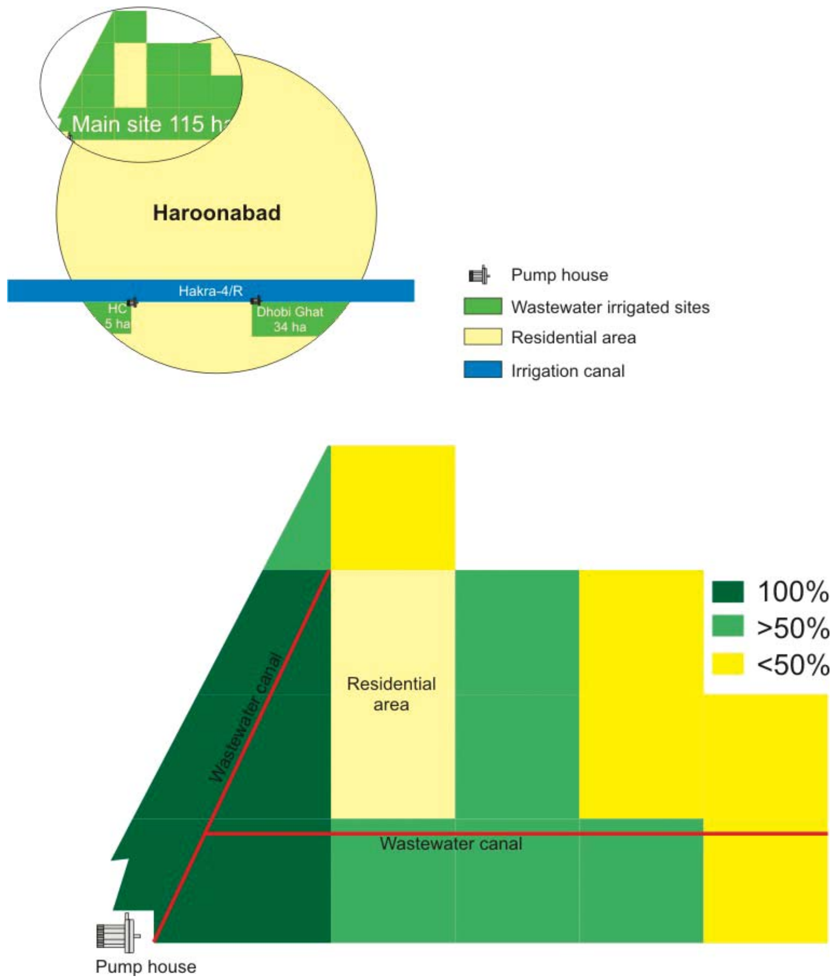


FIGURE 2.
Percentage of wastewater irrigation applications per hectare at the main wastewater disposal site.



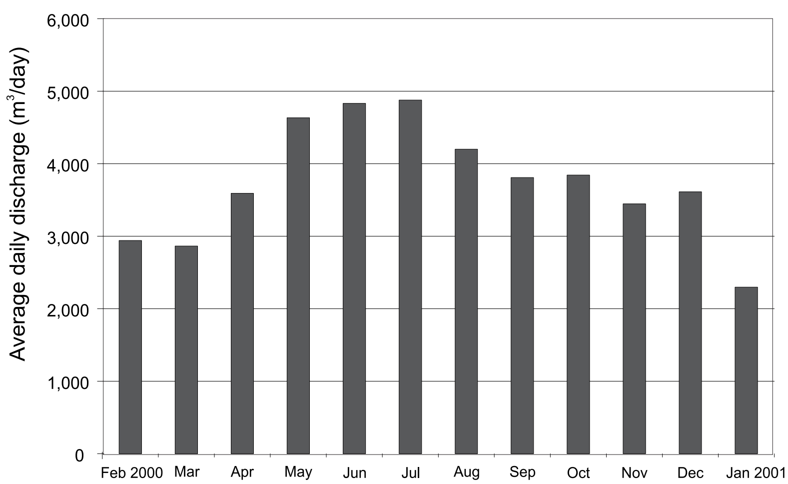
The main crops grown with wastewater were vegetables (in particular cauliflower) cotton and fodder. Vegetables generally received wastewater irrigation twice a week, fodder once a week and cotton once in every three weeks. Cropping intensities from wastewater irrigated fields were nearly 300 percent (three crops per year). On the other hand, fields irrigated with water from the Hakra-4/R distributary had a maximum cropping intensity of 200 percent and the crops grown were wheat, cotton, sugarcane and fodder. Field water application was twice every three weeks to all plots.

Water Supply and Wastewater Discharges

The Hakra-4/R canal, which also supplies water for domestic water uses in Haroonabad, is closed during one week every month. The four large sedimentation tanks of the main water supply scheme of Haroonabad are generally capable of providing water to the town in spite of these interruptions. The annual closure for maintenance in December/January, lasting at least a month, coincides with a lower demand for water in the town. Water shortages are, however, felt in the town as well as in the wastewater-irrigated fields during this period.

At present, three pumps with capacities ranging from 50 l/s to 70 l/s supply wastewater for irrigation. The three sites are the main disposal station site around the old disposal station (115 ha), Dhobi Ghat-site (34 ha), and the housing colony (HC) site (5 ha). The International Water Management Institute (IWMI) monitored the wastewater discharges at the main disposal sites. The readings (figure 3) show a clear peak disposal in the summer months (July, 4,877 m^3/day) when temperatures are highest and people tend to use more water. January, the coldest month and the month of the distributary maintenance, showed the lowest value (2,298 m^3/day) in 2001.

FIGURE 3.
Average daily wastewater discharges for Haroonabad main disposal site.



Material and Methods

Site and Field Selection

Three sites and nine fields were selected to monitor irrigation and nutrient applications and heavy metal build up. The main disposal site had received wastewater over a period of thirty-five years, the Dhobi Ghat site for the past two years and the fields in village 54-4/R had never been irrigated with wastewater. The nine fields were selected on the basis of the percentage of wastewater they received: fully wastewater irrigated, partly wastewater irrigated and non-wastewater irrigated. Other criteria were crop under cultivation and growth stage. Crops grown were cotton, fodder and cauliflower.

Water and Nutrient Balance

For the water balance the following simplified formula was used:

$$ETact = (Pe + Ig + Cr) - (Dr + Dp + Sr)$$

where, *ETact* = Actual Evapotranspiration, *Pe* = ffective Precipitation, *Ig* = Gross Irrigation, *Cr* = Capillary rise, *Dr* = Drainage, *Dp* = Deep percolation and *Sr* = Surface runoff.

Owing to logistical difficulties in conducting a complete nutrient balance estimation, we chose a simple nutrient application evaluation by comparing nutrient applications with those recommended for conditions in Pakistan (Ministry of Food, Agriculture and Livestock 1997). These values are presented in table 1.

Nutrients applied in the form of wastewater or chemical fertilizers that exceeded the recommended amounts were assumed not to benefit crop production or either accumulate in the soil or leach to groundwater.

TABLE 1.
Recommended fertilizer (nutrient) applications for fodder, cauliflower and cotton, according to the Pakistan Ministry of Food, Agriculture and Livestock.

Crop	Nitrogen (total N) kg/ha	Phosphorus (total P) kg/ha	Potassium (total K) kg/ha
Fodder	178	21	62
Cotton	114	30	62
Cauliflower	123	106	101

(Waste)water Applications

From May to September 2000, water deliveries to the nine selected fields were monitored and information on fertilizer use was collected. A cutthroat flume (Siddiqui, Lashari and Skogerboe 1996) was installed at the water entry point in the selected fields to monitor the amount of water applied to the fields. Two research assistants recorded water head and time during the full time of irrigation. To estimate irrigation application fractions, soil moisture content measurements were carried out at four different depths (15 cm, 30 cm, 60 cm and 90 cm) before and after each irrigation event. This was done with a TRIME-FM (Time Domain Reflectometry [TDR], Eijkelkamp, the Netherlands) that gives direct readings on soil moisture content in pre-installed tubes. Each tube represented an area of approximately 1,000 m^2.

Rainfall and runoff from fields did not occur during the period under study. Other meteorological data was obtained from the IWMI Water and Climate Atlas (www.cgiar.org/iwmi/WAtlas/). Groundwater levels were monitored just before and 24 hours after irrigation and on a biweekly basis at 28 piezometers in the monitored fields.

Nutrients and Heavy Metals

(Waste)water was sampled in two 24-hour periods from all three sites. Twelve samples were collected from the main disposal sites, four samples from Dhobi Ghat and two samples from Hakra-4/R. Samples were collected and stored in acid washed plastic bottles and sealed until analysis in the local field laboratory. Samples were taken close to the pump installation.

Nutrient concentrations were analyzed using a portable spectro-photometer (HACH DR/2010, USA) following the standard procedures set in the guidelines (HACH 1997).

Heavy metal analyses in water and soil samples were carried out in the Central High Tech Laboratory, University of Agriculture, Faisalabad. Water samples were filtered through Whatman Filter paper-1 and both filtered sediment and water samples were analyzed for eleven different heavy metals by a Hitachi Z-8200 atomic absorption spectrophotometer.

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 of each depth were composed into one sample and put in a plastic bag. A first set of 36 soil samples was analyzed for all metals traceable with the atomic absorption spectrophotometer in the Central High Tech Laboratory. On the basis of these results the six heavy metals detected—Lead (Pb), Nickel (Ni), Cobalt (Co), Copper (Cu), Manganese (Mn) and Chromium (Cr)—were analyzed in the remaining soil samples.

Data Analyses

Depleted Fractions

The depleted fraction is the share of applied water actually used for evapotranspiration. The remaining fraction is lost to the root zone and not available. As rainfall, run-off and capillary rise (groundwater was always found at least one meter below the root zone) did not occur, deep percolation was the only factor affecting the depleted fraction. Deep percolation, in this study, was defined as water leaving the root zone (depending on the crop) to groundwater or being fixed in a lower soil layer. We assumed that deep percolation would take place within 24 hours after an irrigation application. Deep percolation was therefore calculated as follows: the total irrigation water applied minus water stored in the root zone (calculated by using soil moisture measurements just before and 24 hours after an irrigation application) and minus 24-hour evapotranspiration. Rooting depth values and k_c factors were retrieved from Cropwat-4 for Windows. An irrigation fraction value of 60 percent indicated that 60 percent of the applied water is stored in the root zone of the crop, and is subsequently available for depletion through evapotranspiration.

Nutrient Application Efficiencies

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. Any additional chemical fertilizer application (in most of the cases this happened) was added to the nutrients available through irrigation water. The total application of nutrients was compared with recommended application levels of fertilizer (table1). Total nutrient application divided by recommended nutrient application led to the nutrient application fractions. Values over 100 percent indicate excess while values below 100 percent nutrients indicate deficiency.

Results

Water Quality

The concentration of pollutants measured in wastewater from Haroonabad town (table 2) was within permissible limits according to the Pakistan Environmental Protection Ordinance (annex 1), except for ammonia concentrations which were too high. International health

TABLE 2.
Water quality of regular canal water and wastewater used for irrigation in Haroonabad, Pakistan.

Parameter	Unit	Hakra-4/R water	Wastewater
pH		7.4	6.9
Total dissolved solids (TDS)	mg/l	202	2,076
Electrical conductivity (EC)	dS/m	0.4	4.4
Dissolved oxygen (DO)	mg/l	7.7	2.7
E.coli	Count/100 ml	$1.6\ 10^3$	$6.3\ 10^7$
Helminth eggs	Number/l	n.d..	100
Sodium (Na)	mg/l	46.8	199.0
Calcium (Ca)	mg/l	22.4	29.1
SAR	mg/l	1.0	4.5
Ammonia (NH_3)	mg/l	10.0	97.3
Total Nitrogen (N)	mg/l	8.0	78.3
Total Phosphorus (P)	mg/l	0.2	8.6
Total Potassium (K)	mg/l	7.1	34.7
Magnesium (Mg)	mg/l	37.5	67.6
Manganese (Mn)	mg/l	0.12	0.07
Chromium (Cr)	mg/l	0.03	0.23
Lead (Pb)	mg/l	0.13	0.04
Nickel (Ni)	mg/l	0.17	0.14
Copper (Cu)	mg/l	0.12	0.35
Cobalt (Co)	mg/l	0.09	0.06
Cadmium (Cd)	mg/l	0.02	0.01
Iron (Fe)	mg/l	0.01	0.22
Zinc (Zn)	mg/l	0.10	n.d.

Note: n.d. = no data

guidelines for *E. coli* (< 1,000/100 ml) and for helminth eggs (< 1/liter) made the wastewater unsuitable for agricultural use of any kind. High nitrogen levels in wastewater restricted its use for agriculture (annex 2). It is interesting that Hakra-4/R water with much lower fecal contamination levels was also unfit for irrigation according to the same health guidelines. With the nitrogen levels that were measured in the irrigation canal Hakra-4/R, the water would be placed in the moderate restriction of use category. High nitrogen and *E.coli* counts in Hakra-4/R water could be attributed to wastewater disposal in Hakra-4/R further upstream of Haroonabad. Salinity values for wastewater were very high; Total Dissolved Solids (TDS) as well as Electrical Conductivity (EC) were rated in the "severe restriction on use" group. However, during the course of the study, farmers did not complain that wastewater quality was affecting their crops and they only mentioned that they faced problems with detergents in the wastewater.

Heavy metals fell within the standards set by the Pakistani government for wastewater disposal and only chromium and cobalt concentrations could pose a (minimal) risk to crop growth as they exceeded the maximum permissible concentrations (annex 3).

Irrigation Fractions

Table 3 presents the irrigation applications for the three categories of fields: 100 percent wastewater use, conjunctive use of wastewater and regular (Hakra-4/R) irrigation water and only regular irrigation water. Fields irrigated with regular canal water showed the greatest depth applied per irrigation and this can be explained by the fact that fields receive water only once a week and in some cases even once in every two weeks. This is in contrast to fields that were irrigated with wastewater and that received water at least once a week or, in the case of vegetables, even twice or thrice a week and therefore each application was lower. Fields under conjunctive water use had the lowest, single application depths, probably because these areas were at the edge of the fully wastewater irrigated area and did not always receive wastewater or received only small amounts. Regular canal water supplemented wastewater in these fields.

Depleted fractions, on the other hand, were the highest for conjunctive use. This was so because the larger application depths and the shorter interval between water applications for 100 percent wastewater irrigated fields led to more water percolating below the root zone. Apparently the almost continuous availability of wastewater led to high percolation rates. The sample size was small with relatively small differences between the different water-use categories and the data, therefore, cannot provide conclusive evidence.

Groundwater rise due to overapplication of water could threaten the sustainability of the current wastewater irrigation practices in Haroonabad. The groundwater levels in the period under monitoring dropped considerably. The average difference between groundwater levels in February and September in the 28 piezometers installed at the irrigated sites was 0.71 m (standard deviation 0.33 m). This drop in groundwater levels could, most likely, be attributed to the fact that the whole of Pakistan and particularly the Southern provinces had extremely low rainfall with a complete failure of rainfall during the year 2000 monsoon. Therefore, it was not possible to draw any conclusion on the impact of wastewater irrigation on groundwater levels.

Nutrient Application Efficiencies

Table 4 presents the range of nitrogen, phosphorus and potassium applications per hectare per cropping season. In all cases, nutrients (except for phosphorus in cauliflower grown with conjunctive water use) were overapplied (table 5). In some cases, more than 9 times the recommended rate was applied. This situation becomes even worse if we take into consideration the fact that the guidelines are set for certain

TABLE 3.
Irrigation applications and fractions per application for regular canal water, wastewater and both wastewater and regular canal water (used conjunctively).

	Water applied per irrigation turn (mm)		Irrigation fractions (%)	
	Average	S.D.	Average	S.D.
100% wastewater irrigated	61	29	53	20
Conjunctive water use	47	19	60	13
Hakra 4/R water irrigated	86	14	60	23

S.D. = Standard deviation

TABLE 4.
Maximum and minimum nutrient applications for regular canal water, wastewater and both wastewater and regular canal water used conjunctively.

	Nitrogen Kg/ha		Phosphorus Kg/ha		Potassium Kg/ha	
	Max	Min	Max	Min	Max	Min
100% wastewater irrigated	2,030	740	1,110	420	1,580	765
Conjunctive water use	815	480	1,040	45	570	470
Hakra 4/R water irrigated	Farm yard manure applied once per cropping season					

TABLE 5.
Nutrient application efficiencies per crop type for different water uses.

		Nitrogen %		Phosphorus %		Potassium %	
		Max	Min	Max	Min	Max	Min
Cauliflower	100 % Wastewater	920	220	110	20	395	125
	Conjunctive	420	250	45	25	180	155
Cotton	100 % Wastewater	900	390	440	230	650	210
	Conjunctive	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fodder	100 % Wastewater	905	230	790	180	930	340
	Conjunctive	235	140	190	100	280	225

Note: n.d. = no data

specific periods within the growing season. For example, cauliflower and fodder (sorghum: *Sorghum bicolor*) should receive fertilizers during the time of land preparation and at first irrigation, while for cotton, the time before flowering is critical for nutrient application. The large difference between minimum and maximum nutrient applications could be explained by daily fluctuation—a farmer using wastewater late at night or early in the morning uses wastewater with a lower nutrient value than a farmer who irrigates during daytime.

Farmers using wastewater did not report problems with the crops grown but did mention that they were limited in crop choice because certain crops such as wheat were not considered suitable to grow with wastewater. Some farmers mentioned that cotton was a bad choice although other farmers grew cotton without reporting any problems. All farmers mentioned that they had to use more pesticides due to excessive growth of vegetation, which led to more pest attacks on crops.

Groundwater Quality

Shallow groundwater (<10 meter depth) in the wastewater irrigated and ordinary canal-water irrigated sites was not used for drinking or other domestic purposes. Salinity levels of the natural groundwater exceeded the World Health Organization (WHO 1993) guideline value set for drinking water, making the groundwater unpalatable. The data suggest that wastewater irrigation has led to a further increase of groundwater salinity levels (table 6). Total coliform and *E.coli* counts for groundwater in the wastewater irrigated areas were above that of the ordinary canal-water irrigated sites but both values exceeded the standard of zero coliform and *E.coli,* set for drinking water.

The concentrations of nitrogen compounds (NH_3, NO_3 and NO_2) and *E.coli* counts in groundwater under the wastewater irrigated sites were very high and could pose a health risk if used for drinking. Chromium concentrations at both sites, for unexplained reasons, exceeded the WHO guideline values for drinking water by a factor of 3 but all the other metals were within safe concentrations for drinking water.

Soil Quality

Soil type, for wastewater as well as ordinary canal-water irrigated sites, was sandy loam. Table 7 shows the physical and chemical properties of the soil for different wastewater application intensities.

Soil pH for all three types of irrigation fell within normal ranges for sandy loam soils in Pakistan. Wastewater-irrigated soils show an increased organic matter content when compared to ordinary canal-water irrigated soils in the southern Punjab (SSP and IWMI 1996).

Table 8 shows the average heavy metal concentrations in the first 30 cm of soil at the three different sites. In comparison, the soils irrigated by wastewater contain larger amounts of copper, lead and manganese.

TABLE 6.
Groundwater quality at wastewater irrigated and ordinary canal-water irrigated sites (Hakra-4/R).

Parameter	Unit	WHO* guideline	Hakra-4/R water irrigated	Wastewater irrigated
pH		6.5 – 9.2	7.25	7.25
Electrical conductivity (EC)	dS/m	n.v.g.	2.75	5.37
E.coli	Count/100 ml	0	20	338
Ammonia (NH_3)	mg/l	1.5	13.00	18.68
Nitrate (NO_3)	mg/l	50	47.00	67.89
Nitrite (NO_2)	mg/l	3	0.02	2.57
Manganese (Mn)	ppm	0.5	0.10	0.43
Chromium (Cr)	ppm	0.05	0.15	0.18
Lead (Pb)	ppm	0.01	-	0.01
Nickel (Ni)	ppm	0.02	0.85	0.43
Copper (Cu)	ppm	1.5	-	0.15
Cobalt (Co)	ppm	n.v.g.	0.05	0.05
Cadmium (Cd)	ppm	0.003	-	-
Iron (Fe)	ppm	1.0	0.12	0.15
Zinc (Zn)	ppm	3.0	-	0.55

*WHO 1993 drinking water guidelines

Note: n.v.g. = no value given

TABLE 7.
Chemical and physical soil properties of wastewater irrigated and ordinary canal-water irrigated fields.

	pH	Bulk density (g/cm^3)	Organic matter (%)
Wastewater irrigated	8.01	1.67	0.91
Conjunctive use	8.06	1.60	0.95
Hakra-4/R water irrigated	8.04	1.56	0.67

TABLE 8.
Heavy metal concentrations in the first 30 cm of the soil by type of irrigation water supply.

	Heavy metal concentrations in soil (mg/kg)					
	Co	Cr	Cu	Mn	Ni	Pb
100% Wastewater irrigated	11.6	70.4	66.8	223.6	29.0	16.3
Conjunctive water use	12.7	46.5	55.0	246.4	27.1	9.2
Hakra 4/R water irrigated	11.4	69.7	39.9	196.8	24.2	6.6

Discussion

The wastewater in Haroonabad was clearly not suitable for unrestricted irrigation according to international health guidelines and it would have to be treated to make safe use possible (Mara and Cairncross 1989; Blumenthal et al. 2000). The agricultural guidelines would place slight to moderate restrictions on the use of this water for agricultural production (Pescod 1992).

In the discussion on suitability of wastewater for irrigation, one has to realize that regular irrigation water and river water in Pakistan in most instances does not meet health and agricultural water quality standards (Ensink et al. 2002)—a situation which is common in most semi-arid and arid developing countries (GEMS 2002). The lack of funds for treatment of wastewater leaves many urban centers with only one option, which is disposal of wastewater into open water bodies like rivers and irrigation canals. This suggests that there is a trade-off between use of untreated wastewater—which poses localized health risks to farmers and consumers—and disposal of untreated wastewater in the canal system, which poses health risks to people using the water for domestic purposes, which, in many cases, includes drinking.

Negative Environmental Impacts

One of the negative environmental impacts associated with wastewater use is groundwater contamination through high concentrations of nitrates, salts and micro-organisms (Mara 1977; USEPA 1992). The actual impacts and their importance for future use depend on the local situation. In Mexico, the most immediate threat to public water supply from pollutants originating in wastewater was posed by salinity (Chilton et al. 1998). In contrast, Farid et al. (1993) reported an improvement in the salinity of groundwater in Egypt after years of wastewater irrigation. Nitrates and trace organic chemicals leaching to the groundwater are considered to pose a potential health risk. However, there is very limited documented evidence that these chemicals have been the cause of human disease (Cooper 1991). The leaching of salts, nitrates and microorganisms would be of little concern anyway in areas where groundwater cannot be utilized because of high fluoride, iron, arsenic or salt levels. In these cases the groundwater has no valuable use attached to it (Hussain et al. 2002).

Accumulation of heavy metals proved to be almost negligible, with only increased levels of lead, copper and manganese, even in the fields that had received wastewater for over 30 years. All the current heavy metal concentration levels are unlikely to seriously affect crop production as they were within the ranges of normal soil concentrations (Page and Chang 1985). Sources of these materials have not been identified, but the higher concentration of copper is possibly due to aged copper pipes in the water supply system of the town, while the increased levels of lead could be attributed to exhaust fumes of the bus station which is situated next to the main disposal site (Davies 1997). There is no convincing data that manganese is toxic for humans (Cornish, Mensah and Ghesquire 1999). At the current rate of accumulation the metals would not prove to be a risk for the coming decades. At the current expansion rate of Haroonabad, it is likely that the wastewater irrigated sites will be transformed to residential areas by that time. It seems apparent that, in future decision-making with regard to the use of wastewater for irrigation, a distinction needs to be made between industrialized cities and cities with mainly domestic wastewater.

Irrigation Fractions

Irrigation fractions are an important tool to assess the success of irrigation practices. The present irrigation fractions in Haroonabad reveal an over application of water and nutrients through wastewater. Almost half of all wastewater applied at field level percolates below crop roots, an application fraction that is low according to Pakistani standards. To the authors knowledge no other figures on nutrient application efficiencies through wastewater are available for Pakistan or other countries and it is therefore not possible to place the "Haroonabad" nutrient efficiencies in a wider context. The irrigation fractions and nutrient efficiencies show that the current wastewater irrigation scheduling is not crop demand driven but based on fixed allocations decided by a relatively small group of farmers. Better conjunctive use of wastewater and regular canal water would lead to improved nutrient efficiencies, improved wastewater fractions and an expansion of the current area under wastewater irrigation.

Conjunctive Water Use, Diluting the Risks and Spreading the Benefits

In table 9, four different scenarios of conjunctive water management are presented. In the calculations the assumption has been made that improved irrigation fractions would be possible if more farmers could have access to wastewater, a certain margin of overapplication (30%) of wastewater has although been included as this might guarantee the sustainability of wastewater use because of leaching of nutrients, salts and other wastewater constituents. Due to the limitations of the nutrient balance set-up, we were not able to correct for the fact that improved depletion fractions will lead to improved nitrogen application efficiencies. The fact that the normal irrigation infrastructure is still present and farmers

TABLE 9.
Irrigated area under different conjunctive water management scenarios.

	Water fraction	Average nutrient fraction	Irrigated area (ha)*	Average nutrients application per cropping season through wastewater (kg/ha)		
				N	P	K
Current practice	47	570	85	1385	765	260
Scenario1	70	570	105	1385	765	260
Scenario 2	47	285	170	690	380	130
Scenario 3	70	285	210	690	380	130
Scenario 4	70	140	420	345	190	65

*Only the 100% wastewater irrigated sites are used in this table
Notes: Scenario 1 = Improved irrigation efficiency
Scenario 2 = One normal water application followed by one wastewater application.
Scenario 3 = Scenario 1 + Scenario 2.
Scenario 4 = Scenario 1 + three normal water applications followed by one wastewater application

can still claim canal water rights makes conjunctive water use a feasible option for many Pakistani cities.

In Haroonabad under ideal conditions of improved irrigation fractions and three canal water turns (scenario 4), the wastewater-irrigated area could be expanded by 335 hectares. On the basis of existing average farm size, this means that an additional 300 farmers would benefit from wastewater and at the same time be exposed to it.

Protective gear, like boots and gloves, are unlikely to find wide acceptance because of climatic conditions. Additional health measures like regular treatment with anti-worm medication and improved hygiene should be implemented. The local municipality, through its communicable disease control officers, should take a leading role in promoting these measures.

The economic component of the Haroonabad study showed that the average farm income per year of wastewater farmers was considerably higher than that of regular canal-water farmers (van der Hoek et al. 2002). Based on the calculations, the conjunctive use of wastewater, and the concurrent expansion of the wastewater irrigated area would lead to an additional farm income of around Rs 3 million (US$50,000) per year, which would make investments by local farmers and municipalities in additional infrastructure a feasible option.

The water fraction and nutrient efficiency formulas used are simplified versions where, for example, soil processes like de-nitrification and nutrient up-take have not been taken into account. A water and nutrient balance that accounts for these processes could serve as input to a model, which could predict nutrient buildup in soil and groundwater, and uptake by the crop, enabling, for example, the determination of the right conjunctive use of the different water sources.

Conclusion

Farmers in Pakistan and many other countries consider wastewater a valuable resource because of its high productivity and profitability. The reality is that farmers will take health risks and will use wastewater when there is an opportunity for direct economic benefits. The municipal councils in Pakistan are aware of the value of wastewater and sell it to farmers, using the revenue to keep other utilities working. All stakeholders consider this to be a win-win situation—with very few incentives to invest in treatment facilities. Therefore, rather than concluding that treatment facilities should be provided or strict legislation enforced, we suggest that there is a need to look at other options than wastewater treatment, to minimize the negative impacts of untreated wastewater irrigation, and come up with realistic alternatives for wastewater treatment under the given set of social and economic conditions.

In the case of small towns and cities without major industry, the environmental risks of soil contamination and plant uptake of heavy metals seem to be negligible. In places where groundwater is not used for consumption, groundwater contamination is not an issue and in these instances conjunctive use of regular irrigation water and wastewater will reduce the environmental impact of wastewater use and allow a larger group of farmers to benefit from wastewater use.

Dilution of wastewater with regular canal water will lead to lower coliform and worm egg counts, but these will in most cases remain too high according to WHO guidelines; conjunctive use of wastewater should therefore be practiced in combination with anti-helminth-treatment and other health protection measures.

The sustainability, and agronomic and financial gains make conjunctive use an attractive option for farmers. However, conjunctive use of wastewater will require changes in farm practices and a willingness, by those that have an exclusive access to wastewater, to share the wastewater resource with other farmers. Fluctuations in nutrient concentrations will demand community and municipality involvement as it would require storage so that, through proper mixing of both water sources, a “standard” nutrient load can be provided. The financial gains that can be obtained through conjunctive use of wastewater would make investments in new infrastructure and treatment programs justifiable.

Annex 1

Maximal permissible limits for municipal and liquid industrial effluent discharges in Pakistan (UNESCAP 2000).

Parameter	Permissible limit (mg/l)	Parameter	Permissible limit (mg/l)
Temperature (°C)	40	Cadmium	0.1
pH (-)	6-10	Chromium	1
BOD_5 at 20 °C	80	Copper	1
COD	150	Lead	0.5
Total suspended solids (SS)	1,150	Mercury	0.01
Total dissolved solids	3,500	Selenium	0.5
Grease and oil	10	Nickel	1
Phenol compounds	0.1	Silver	1
Chloride (Cl)	1,000	Total toxic metals	2
Fluoride (F)	20	Zinc	5
Cyanide (CN)	2	Arsenic	1
Anionic detergents	20	Barium	1.5
Sulphate (SO_4)	600	Iron	2
Sulphide(S)	1	Manganese	1.5
Ammonia (NH_3)	40	Boron	6
Pesticides, herbicides, etc.	0.15		

Annex 2

Guidelines for interpretation of water quality for surface irrigation (Pescod 1992).

Parameter	Unit	Degree of restriction		
		None	Slight to Moderate	Severe
Salinity				
TDS	mg/l	<450	450 – 2000	>2000
EC	dS/m	< 0.7	0.7 – 3.0	> 3.0
Specific Ion toxicity				
Sodium (Na)	SAR	<3	3 – 9	>9
Miscellaneous				
Nitrogen (NO_3-N)	mg/l	<5	5 – 30	>30
pH			Normal range 6.5 – 8.4	

Annex 3

Threshold levels of trace elements in irrigation water for crop production, based on 10,000 m^3 per ha per year (Pescod 1992).

Element		Recommended Maximum Concentration (mg/l)
Al	Aluminium	5.0
Cd	Cadmium	0.01
Co	Cobalt	0.05
Cr	Chromium	0.10
Cu	Copper	0.20
Fe	Iron	5.0
Mn	Manganese	0.20
Ni	Nickel	0.20
Pd	Lead	5.0
Zn	Zinc	2.0

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