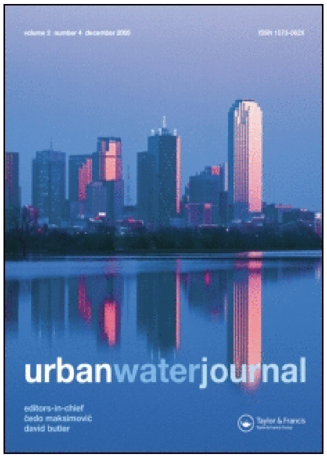

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Waste stabilization pond performance in Pakistan and its implications for wastewater use in agriculture

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Faisalabad is one of the few cities in Pakistan that has a waste stabilization pond (WSP) system. Local farmers complained about the high salinity and low nutrient value of the final effluent from the WSP and preferred the use of untreated wastewater. A one-year study showed a strong increase in salinity from untreated wastewater to final effluent with a clear decline in nitrogen concentration, thereby confirming farmer perceptions. The performance of the WSP was poor and did not comply with World Health Organization (WHO) and Food and Agricultural Organization (FAO) guidelines for irrigation water. The poor performance of the WSP could be attributed to a combination of factors: poor design, the extreme climatic conditions and the large quantities of untreated wastewater which were used in agriculture. In countries such as Pakistan where the use of untreated wastewater has a long history, farmer perceptions should play a pivotal role in the selection of suitable wastewater treatment systems.

Keywords: Climate; Helminths; Nutrients; Pakistan; Salinity; Waste stabilization ponds; Wastewater irrigation

1. Introduction

Pathogens, together with biological and chemical pollutants, form the greatest obstacle to the use of wastewater for agricultural crop irrigation. As a result, the World Health Organization (WHO) has set a strict water quality guideline of ≤1 helminth egg/l in order to protect public health (WHO 2006). Additionally a tolerable burden of waterborne disease of $\leq 10^{-6}$ disability-adjusted life years (DALY) loss per person per year (pppy) for the unrestricted use (irrigation of crops that are consumed uncooked) of wastewater in agriculture has been set (WHO 2006).

A common recommended wastewater treatment method for use in arid and semi-arid developing countries is a system of waste stabilization ponds (WSPs). A national survey conducted in Pakistan revealed that less than 2% of all cities with a population greater than 10 000 inhabitants had any form of wastewater treatment and that in 80% of the cities surveyed, untreated wastewater (hereafter referred to as wastewater) was used for crop irrigation (Ensink *et al.* 2004). Faisalabad, a large (over 2 million inhabitants) industrialized city, was one of the few cities which had an operational wastewater treatment plant. However, WSP effluent was discharged into a storm water drain, while a substantial fraction of the wastewater was taken by local farmers from the main sewer immediately before entering the WSP and used for agricultural purposes. Peri-urban farmers claimed that final effluent (hereafter referred to as

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effluent) was less suitable than wastewater as they perceived it to have a much lower nutrient concentration and a higher salinity. Those peri-urban farmers stated that the use of wastewater resulted in a lower application of inorganic fertilizer and, because of these savings, higher farm incomes. They were consequently unwilling to use effluent from the WSP.

As WSP remains the standard wastewater treatment method for low-income countries such as Pakistan, we considered it important to investigate farmers' claims about the unsuitability of effluent for use in agriculture because of low nutrient concentration and high salinity. We also evaluated the treatment performance of the WSP with respect to parameters of public health importance.

2. Methodology

2.1 *Waste stabilization ponds*

The WSP in Faisalabad is located in a predominantly agricultural area and has been in operation since January 1998. It covers an area of almost 100 ha and consists of six parallel anaerobic ponds and two series each comprising one facultative pond and two maturation ponds (figure 1). The plant was designed for a wastewater flow of 90 000 m^3/d with an average biochemical oxygen demand (BOD) of 380 mg/l. BOD removal at the design stage, based on a total hydraulic retention time (HRT) of 16.5 days (table 1) and calculated following standard procedures, was determined to be 88% (WASA 1993). This would result in an effluent with BOD in compliance with the Pakistan Environmental Protection Agency's standard for the disposal of municipal and industrial wastewater effluents which is set at ≤80 mg/l (UNESCAP 2000).

Based on the design parameters the anaerobic ponds would require desludging every 3 years. In the design, the reaction rate coefficient for the anaerobic ponds was calculated based on the mean daily temperature during the coldest month, for which 20°C was taken, while the hydraulic retention time was set for 3 days. According to the design calculations this would have resulted in an effluent quality from the anaerobic ponds of 115 mg/l BOD.

2.2 *Wastewater irrigation*

Wastewater is pumped on a 24 h basis from the main sewerage network into a primary drain bringing wastewater to the WSP. Local farmers, with permission from the local Water and Sanitation Authority (WASA), have installed five permanent outlets to convey untreated wastewater to their existing irrigation networks. Approximately 290

Table 1. Layout and design characteristics of the WSP in Faisalabad.

	n		Area (m)	Depth (m)	HRT (days)
Anaerobic pond	6	Parallel	100 × 150	3 + 1 (sludge)	3
Facultative pond	2	Seri	450 × 300	1.5	4.5
Maturation pond	4	Seri	450 × 300	1.5	4.5
Total	12				16.5

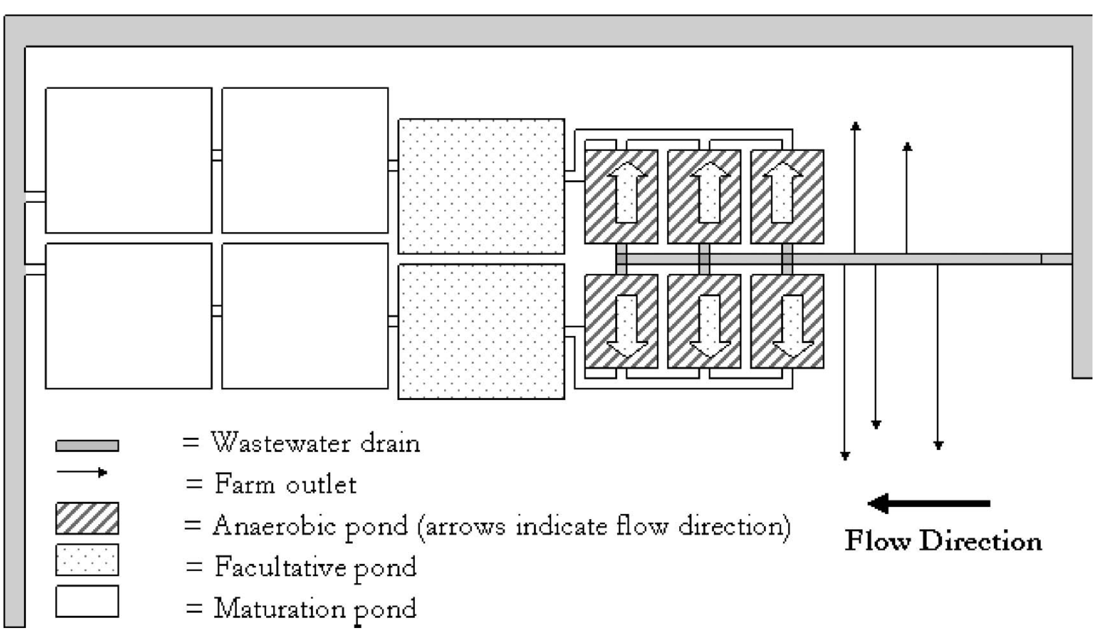

Figure 1. Layout of the waste stabilization ponds in Faisalabad (not to scale).

farming households paid annual fees totalling 440 000 Pakistan rupees (USD 7500) to the WASA to use wastewater. The main crops cultivated with wastewater were fodder, wheat and vegetables. The vegetables included: spinach, cauliflower, aubergine, chillies and tomatoes.

2.3 *Water quality and discharge measurements*

During the 12-month period from September 2001 to August 2002 wastewater flows in the primary drain were measured fortnightly and the qualities of the wastewater and final effluent were determined monthly. Discharge measurements were taken after each point where wastewater was taken from the primary drain to determine the inflow to the WSP and the volume of wastewater used for irrigation. Cross-sections were determined at appropriate points along the drain and a propeller meter (Scientific Instruments Inc., Milwaukee, USA) was used to measure the flow velocity at each of the selected cross-sections.

Wastewater samples were collected from the wastewater drain immediately upstream of the inlet into the WSP. Effluent samples were collected from the final ponds prior to discharge into the disposal drain. A 5-litre sample was collected for the analysis of helminth eggs as specified in the modified Bailenger method (Ayres and Mara 1996). Four additional water samples were taken at each point to determine BOD, *E. coli*, total nitrogen (TN) and total phosphate (TP) concentrations. *E. coli* counts were determined by membrane filtration with a commercial medium, m-ColiBlue24® (HACH, Loveland, USA) BOD analysis was conducted on a BODTrak™ (HACH, Loveland, USA) using the respirometric method (HACH 1997). Nutrient concentrations were analysed using a portable spectrophotometer (DR/2010, HACH, Loveland, USA). For total nitrogen the persulphate digestion method was used and the molybdovanadate with acid persulphate digestion method for total phosphate (HACH 1997). Salinity (expressed as electrical conductivity (EC)) and pH were determined on-site, using hand-held meters (EC: CO150, HACH, Loveland, USA; pH: Hanna instruments, Woonsocket, USA).

2.4 *Climatic data*

Temperature, rainfall and evaporation data were obtained from the Government of Pakistan meteorology station in Faisalabad.

2.5 *Data analysis*

Data analysis was undertaken using Microsoft Excel (Microsoft Cooperation, Redmond, USA). Arithmetic means and 95% confidence intervals (CI) were calculated for most water quality parameters, with the exception of *E. coli* concentrations, for which the geometric was calculated. Differences in concentrations between wastewater and effluent were compared using a paired, two-sided student *t*-test. A *p*-value of less than 0.05 was considered significant.

3. Results

3.1 *Wastewater disposal and use*

The daily flow in the drain conveying the wastewater to the WSP ranged from 71 300 m^3/d to 94 300 m^3/d and was on average 12% below the flow for which the WSP was designed (table 2). The volumes of wastewater used for irrigation and wastewater treated in the WSP were highly variable, with on average 42 100 m^3/d of wastewater utilized for irrigation and 37 200 m^3/d of wastewater entering the anaerobic ponds. Significantly less wastewater was utilized by the farmers during September – November 2001 owing to a disagreement over the price of the wastewater which resulted in the temporary closure of one of the irrigation canals. The lower-than-designed flow, compounded by the utilization of much of the wastewater, resulted in a hydraulic retention time which was on average 27 days longer than the design specification of the plant (table 1).

3.2 *Wastewater and final effluent water quality*

3.2.1 Helminth eggs and *E. coli*. Wastewater was found to contain high concentrations of helminth eggs and *E. coli* (table 3). Hookworm (*Ancylostoma duodenale* and *Necator Americanus*) was the predominant helminth, followed by

Table 2. Monthly variations in daily wastewater (WW) flow, agricultural wastewater use and wastewater flow in the WSP in the period September 2001 – August 2002.

	Total WW-flow (m^3/d)*	WW used in agriculture (m/d)	WW-inflow into WSP (m/d)*	Total HRT (d)
September	71 300 (79%)	25 700	45 600 (51%)	32.5
October	77 700 (86%)	29 200	48 500 (54%)	30.5
November	82 700 (92%)	23 500	59 200 (66%)	25.0
December	71 500 (79%)	44 200	27 300 (30%)	54.5
January	81 600 (91%)	42 800	38 800 (43%)	38.5
February	81 000 (90%)	46 800	34 100 (38%)	43.5
March	83 600 (93%)	52 300	31 400 (35%)	47.5
April	74 300 (83%)	50 600	23 700 (26%)	62.5
May	71 700 (80%)	49 500	22 200 (25%)	67.0
June	78 200 (87%)	45 600	32 600 (36%)	45.5
July	84 100 (93%)	51 400	32 700 (36%)	45.5
August	94 300 (105%)	44 400	49 900 (55%)	29.5
Mean	79 300 (88%)	42 100	37 200 (41%)	43.5

*Values in parentheses are % of the design inflow for the WSP.

Table 3. Health related water quality parameters for untreated wastewater and final effluent for the period September 2001 – August 2002, in Faisalabad, Pakistan.

		Wastewater		Effluent		Removal†
		Mean	95% CI	Mean	95% CI	(%)
*E. coli**		2×10^7	$1 \times 10^7 - 5 \times 10^7$	1×10^4	$3 \times 10^3 - 3 \times 10^4$	3 Log
Helminths						
Ascaris	eggs/l	142	71 – 212	21	0 – 49	83 (33)
Hookworm	eggs/l	558	168 – 949	704	231 – 1,177	− 148 (404)
BOD	mg/l	394	348 – 440	110	84 – 135	72 (10)
EC	dS/m	2.0	1.4 – 2.6	3.7	3.1 – 4.3	− 90 (38)
pH		7.0	6.8 – 7.2	7.7	7.3 – 8.1	− 10 (4)
TN	mg/l	42	37 – 46	18	12 – 23	58 (18)
TP	mg/l	6.0	5.2 – 6.8	4.1	3.4 – 4.7	32 (11)

*Geometric mean, reported as colony forming units (CFU) 100/ml.
†Negative removals indicate that concentrations in final effluent were higher than those in untreated wastewater.

Ascaris lumbricoides (*Ascaris*), while *Trichuris trichiura* (*Trichuris*) and other helminth eggs were not detected in wastewater throughout the period under study. No significant difference ($p = 0.91$) in helminth egg concentration between effluent and wastewater was detected. Effluent was never found to be free of helminth eggs, and during 4 months of the year helminth egg concentrations in effluent were found to be higher as those in wastewater. However, *Ascaris* and hookworm, showed different trends as *Ascaris* concentrations in effluent were found to be significantly ($p = 0.004$) lower as compared to those in wastewater, while no significant ($p = 0.51$) difference between effluent and wastewater was found for hookworm concentrations. *Ascaris* removal ranged from 66% to 100% for all but one month, during which no removal was achieved. For hookworm full removal was never achieved as removal efficiencies ranged from − 1300% to 86%.

E. coli concentrations in effluent were consistently lower ($p = 0.03$) than those found in wastewater, though removal was low and ranged from 3 Log to 5 Log. The lowest *E. coli* concentration (200 *E. coli*/100 ml) and highest removal was achieved in the month of May when the HRT was longest (65 days).

3.2.2 BOD, salinity and nutrients. BOD concentrations in wastewater fluctuated greatly, with the highest concentrations observed during the winter months (November – March) and the lowest concentrations during the hottest month of the year (May) and during the monsoon season (July – August). Over the year the average BOD concentration was found to have slightly exceeded the design BOD concentration of 380 mg/l (table 3). Effluent had significantly ($p < 0.001$) lower BOD concentrations as compared with wastewater, but the target BOD concentration of 80 mg/l for effluent was only achieved during 2 months.

There was a strong correlation ($r^2 = 0.79$) between BOD and TN concentrations and a slightly weaker ($r^2 = 0.72$) correlation was found between BOD and TP concentrations. Nutrient removal therefore followed a similar pattern as BOD removal, though the difference between TP concentration in wastewater and effluent were found to be borderline ($p = 0.06$) non-significant.

Salinity levels in wastewater were relatively high, with a mean concentration of 2.0 dS/m (table 3). Figure 2 shows that salinity levels in the effluent were found to be consistently and significantly ($p < 0.001$) higher than those in wastewater. This increase in salinity was on average 90% but ranged from 32% to 168%.

3.3 *Climate*

Temperatures in Faisalabad ranged from a minimum of 3°C in January to a maximum of 47°C in May, while the mean daily temperature during the coldest month (January) was 13.5°C. Total annual pan evaporation (1992 mm/y) was found to be 10 times higher than the annual precipitation (190 mm/y), with pan evaporation being especially high (9.9 and 10.8 mm/d) in May and June.

4. Discussion

4.1 *Health implications of wastewater quality used in agriculture*

Wastewater was clearly unfit for the use in agriculture, however so was effluent (WHO 2006). Although most crops that were cultivated in Faisalabad were not consumed uncooked, tomatoes were commonly grown and these, are occasionally consumed uncooked and wastewater should thus comply with the unrestricted use guidelines. Based on the ‘old’ WHO faecal coliform guideline of <1000 *E. coli*/100 ml (WHO 1989) final effluent was unfit for unrestricted irrigation for all but one month (May) of the period

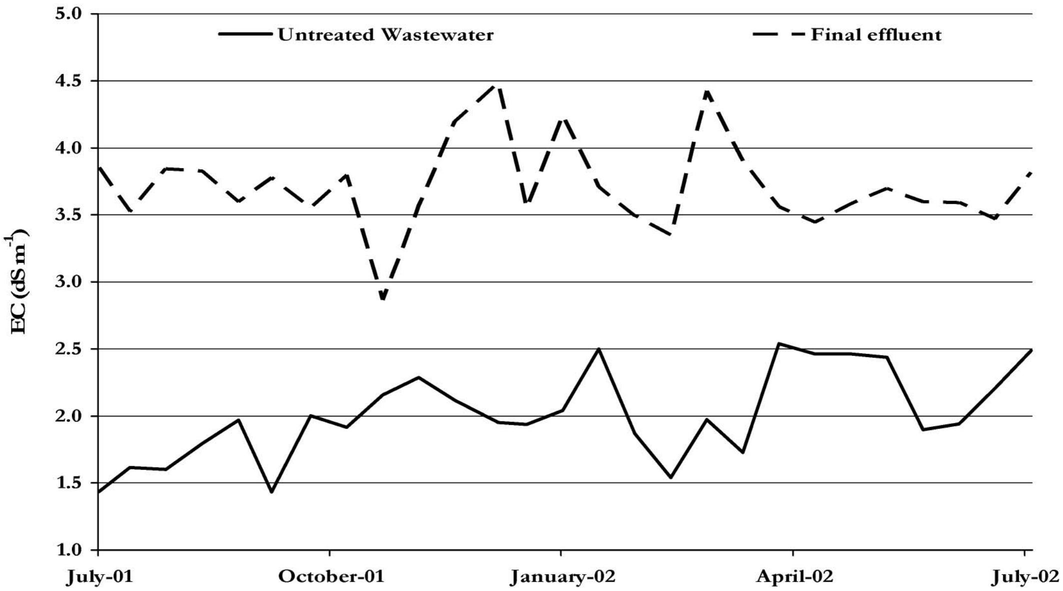

Figure 2. Salinity, expressed as electrical conductivity (EC) in untreated wastewater and final effluent.

under study. While based on the 'new' WHO guidelines additional risk reduction measures, in addition to wastewater treatment, would be needed to allow for unrestricted use (WHO 2006).

4.2 *WSP treatment performance*

WSP have been primarily designed for the removal of BOD and pathogenic bacteria (Arthur 1983, Stott *et al.* 1994). Mara and Cairncross (1989) however assumed that a well designed WSP would also remove all helminth eggs. Helminth egg removal in this survey showed a dual picture; *Ascaris* egg removal was generally good, while hookworm egg removal was very poor. A*scaris* egg removal conformed to past findings (Madera *et al.* 2002, Mara and Silva 1986, Stott *et al.* 1994). Hookworm eggs have a lower settling velocity than *Ascaris* eggs (Stott 2003) and past studies in WSP with a HRT ranging from 16 to 23 days have found hookworm eggs or larvae in final effluent when *Ascaris* eggs was no longer detected (Klutse and Baleux 1995, Lakshminaruyana and Abdulappa 1972, Mara and Silva 1986). These studies however reported hookworm egg removal efficiencies of over 90%, which were never achieved in this study. Besides hookworm, *E. coli*, BOD and TN also showed poor removal efficiencies. *E. coli* removal in the WSP, with a mean removal efficiency of 3 Log *E. coli* was 2 Log lower as could be expected from a well designed WSP (Mara 1997). BOD removal was lower than was calculated in the design and consistently lower than can be expected from a well-designed WSP which should be over 90% (Mara 1997). The low BOD and pathogen removals were especially surprising considering the reduced inflow and the much longer HRT than designed for.

4.3 *Possible explanation for poor treatment performance*

4.3.1 Design. The usual design parameter for anaerobic ponds is the mean air temperature in the coldest month, which determines the reaction rate coefficient and BOD removal (Mara 1997). In the design phase of the WSP this temperature was set for 20°C, however the mean daily temperature for the coldest month during this survey was 13.5°C. The BOD removal efficiency of the WSP, permitted and actual BOD loading for the facultative and maturation ponds was recalculated using standard design formulae (Mara 1997) for 13.5°C and 20°C. Table 4 shows a much lower BOD removal, for both temperatures, than was calculated during design. Poor design has plagued the success of WSP in several countries (Oakley *et al.* 2000) and the results of this survey highlight again to need to follow proper design calculations and further emphasise the need for the collection of accurate climatic data.

Facultative ponds should receive a relatively low BOD surface loading as the overloading of these ponds will prevent the development of healthy algal populations which are key to BOD removal in facultative ponds. Overloading of facultative ponds could have been prevented by the construction of additional parallel ponds.

4.3.2 Hydraulic retention time. The use of large quantities of wastewater resulted in HRT which during some months of the year were more than four times the design value. Research has shown that an increase in HRT in

Table 4. BOD effluent from the three pond types and actual and permitted (in parentheses) volumetric BOD loading of the facultative and maturation ponds at 13.5°C and 20°C assuming a BOD of 380 mg/l in untreated wastewater.

		Facultative Pond		Maturation Pond-1		Maturation Pond-2		
Design	Anaerobic Pond Effluent (mg/l)	Loading (kg/ha/d)	Effluent (mg/l)	Loading (kg/ha/d)	Effluent (mg/l)	Loading (kg/ha/d)	Effluent (mg/l)	BOD removal WSP
20°C	152	506 (250)	107	385 (175)	88	317 (175)	73	81%
13.5°C	201	724 (144)	153	551 (108)	126	454 (108)	104	73%

anaerobic ponds does not automatically lead to a further improved BOD removal (Mara 1997); however, long HRT should have promoted the reduction of *E. coli* and helminth concentrations (Ayres *et al.* 1992). Studies into the poor performance of WSP in Brazil and Mexico suggested that wind speed and wind direction could negatively influence the performance of a WSP by reducing the HRT in some cases by almost 75% (Lloyd *et al.* 2003, Meneses *et al.* 2005). In Faisalabad the predominant wind direction was south east, which was in the same direction as the flow direction of the maturation and facultative pond and this could have significantly shortened the HRT. Hydraulic short-circuiting was further promoted by the position of the inlets and outlets, which were placed directly opposite each other.

4.3.3 Sampling. Although the results of the water quality survey clearly indicate that the WSP in Faisalabad was performing poorly, it remains unclear how poorly they were actually performing. The survey found large fluctuations for the different water quality parameters between the different months and this, combined with the large wastewater withdrawals (increasing the HRT) and wind speed (reducing the HRT), makes it nearly impossible to link wastewater and effluent concentrations and to determine an accurate removal efficiency.

4.4 *Agricultural implications of wastewater and effluent quality*

The most commonly irrigated crops in Pakistan: wheat and cotton, have a relatively high salt tolerance with 6.0 dS/m and 7.7 dS/m respectively, though other crops like rice (3.0 dS/m), cauliflower (1.8 dS/m), spinach (3.2 dS/m) and tomatoes (0.9 dS/m) are more sensitive (Rhoades *et al.* 1992). The use of wastewater in Faisalabad will therefore limit crop diversity as it has shown to do in other areas of Pakistan (van der Hoek *et al.* 2002). However, the use of effluent, with consistently higher salinity concentrations, would place even greater restrictions on its use in agriculture.

The extended HRT in combination with climatic conditions had a negative impact on the salinity of the effluent. In May evaporation resulted in a water loss of 8,750 m^3/d from the facultative and maturation pond (40% of daily inflow) and this would have increased the salinity of the effluent by a corresponding 67%. Increased salinity in final effluent has been reported as a drawback of WSP (Mara 2000); however, few studies have documented the extent of the increase; therefore the increase in salinity found in Faisalabad can not be compared with situations elsewhere.

Both nitrogen as well as phosphate concentrations in wastewater were found to be high, with the nitrogen concentration exceeding the guideline value set by the FAO (Pescod 1992). As might be expected, nitrogen and phosphate concentrations in effluent were lower. The removal of nutrients from wastewater tended to follow a similar trend to that for BOD removal; nitrogen removal was lower than has been reported for other WSP under similar conditions, while phosphate removal was within the lower range of normal removal performance (Mara 1997).

The results of the nationwide wastewater survey in Pakistan and studies in other parts of the world showed that the nutrient value was one of the key incentives for farmers to use wastewater (Ensink *et al.* 2004, Scott *et al.* 2004). The lower nutrient concentrations that were found in effluent, even though they fell within the FAO guideline values, were seen by farmers as a serious drawback for the use of final effluent as they felt that this would have meant an increased need for fertilizer and thus lower farm income.

5. Conclusions and recommendations

The results of the present study clearly support farmers' claims that effluent was less suitable for use in agriculture than wastewater. The WSP in Faisalabad was constructed with the aim to provide safe water for use in agriculture, something which it never did. In retrospect one could question whether the financial investment to construct a WSP was a sound decision, especially considering the fact that the effluent is currently discharged into a sewage drain, while farmers, through extensive and expensive court battles, have won the right to use wastewater. The large wastewater withdrawals undermined the performance of the WSP and thus further confirmed farmer's views that effluent was unsuitable for use in agriculture. The WSP in Faisalabad performed poorly, partly as a result of wastewater withdrawal by farmers and partly as a result of faulty design and the use of incorrect climatic data.

WSP have an important role in supplying agriculture with a safe 'new' water source. However, in areas where wastewater has been used for prolonged periods by farmers, with clear financial gains, their views are paramount and should be taken into account when wastewater treatment technology is selected. Further when wastewater is expected to be used in agriculture the impact of climatic on effluent should be taken into consideration, especially into those areas like Pakistan, where groundwater has a natural high salinity.

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