

## Sewage disposal in the Musi-River, India: water quality remediation through irrigation infrastructure

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**Abstract** The disposal of untreated urban sewage in to open water bodies is common in most developing countries. This poses potential negative consequences to public health and agricultural sustainability. Hyderabad, one of India's largest cities, disposes large amounts of its wastewater untreated into the Musi River, from where it is used, with the aid of irrigation weirs, for agricultural production. This paper presents a 14 month (December 2003 – January 2005) water quality survey which aimed to quantify spatial and temporal changes in key water quality parameters along a 40 km stretch of the Musi River. The survey found that river water quality improved dramatically with distance from the city; from untreated sewage in the city to irrigation water safe for use in agriculture 40 km downstream of the city. This improvement was contributed to by different treatment processes caused or aided by the irrigation weirs placed on the river.

**Keywords** Agriculture · Helminths · India · Musi River · Wastewater use · Wastewater treatment

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## Introduction

Rapid and uncontrolled urbanization is often associated with environmental contamination, especially the pollution of surface water bodies like rivers and lakes by solid and liquid wastes. Large scale pollution of rivers has resulted in strict enforcement of waste disposal legislation in most industrialized countries, where wastewater is disposed of only following extensive treatment. This is in contrast to most developing countries where most sewage goes untreated; in India for example, it is estimated that over 70% of all wastewater is disposed of untreated and that an investment of US\$ 65 billion would be needed to treat all wastewater (Kumar 2003). The situation in India is likely to deteriorate even further as India's population will grow by almost 400 million people in the next quarter of a century, with approximately 85% of this growth taking place in cities (UNPD 2003).

Rivers have a natural, though limited, capacity to restore water quality to pre-pollution levels, through dilution, die-off, sedimentation and biological processes. These natural treatment processes can be further aided by weirs and/or reservoirs on rivers which reduce flow velocities, thereby lengthening hydraulic retention and promoting sedimentation. However with the growth of cities the amount of wastes disposed into rivers often grows beyond their self-purifying ability. In these instances untreated wastewater disposal poses serious risks to public health, and in areas where river water is used for irrigation, to agricultural sustainability.

The Musi River, a tributary of the Krishna River in Andhra Pradesh, India receives large quantities of untreated sewage from the city of Hyderabad. Downstream of the city, Musi water is retained in large and small reservoirs with the help of weirs and from there diverted into irrigation canals and village tanks to be used by farmers for crop production. A clear improvement in river water quality, both in appearance and smell, was observed with increased distance from the city. This raised the hypothesis that the weirs on the river had created waste stabilization ponds (WSP) and aided the river's self purifying ability and could thus provide irrigation water safe for use in agriculture.

This paper presents the results of a water quality survey conducted over a 40 km transect of the Musi River downstream of the city of Hyderabad. The objectives were two-fold: i) to determine spatial and temporal variations in *E. coli* and helminth egg concentrations; key indicator organisms included in the World Health Organization (WHO) guidelines for the safe use of wastewater in agriculture (WHO 2006), ii) to determine the degree of pollution remediation occurring as the combined result of natural river processes and irrigation infrastructure along the river.

## Methodology

### Study area

The Musi River is located on the Deccan Plateau in the State of Andhra Pradesh, Southern India. It originates 60 km upstream of the city of Hyderabad and enters the Krishna River 200 km downstream of it. In the 1920s two large reservoirs were created upstream of Hyderabad to meet the city's increased (drinking) water demand and to mitigate the effect of frequently occurring floods. Due to increased demand for drinking water by the city, no controlled water releases from the reservoirs occur and the river downstream of the reservoir and upstream of Hyderabad is dry.

In the city the river reappears as a result of the large scale sewage disposal into the river bed. Hyderabad has a population of 6.8 million (van Rooijen et al. 2005) and it is estimated

to use over 800,000 m<sup>3</sup> of water per day, while 70% of the city is connected to a sewerage system (HUDA 1994). The city in 2005 had one functioning secondary treatment plant, which treated an estimated 5% of all wastewater produced by the city. All wastewater produced by the city was disposed of into the Musi River and as a result the river had effectively become the city's one and only sewage outfall drain.

The Musi River traditionally provided farmers downstream of Hyderabad with irrigation water for the cultivation of paddy during and after the monsoon rains. Through the construction of weirs, river water is retained in large and small reservoirs on the river from where it is diverted through irrigation canals to village tanks and agricultural fields. There are a total of 22 weirs situated on the Musi River irrigating an area of approximately 10,000 hectares (Katta 1997). In the rural areas the main crop is rice (*Oryza sativa*), while close to the city the main crop is fodder grass (*Brachiaria mutica*).

## Water quality assessment

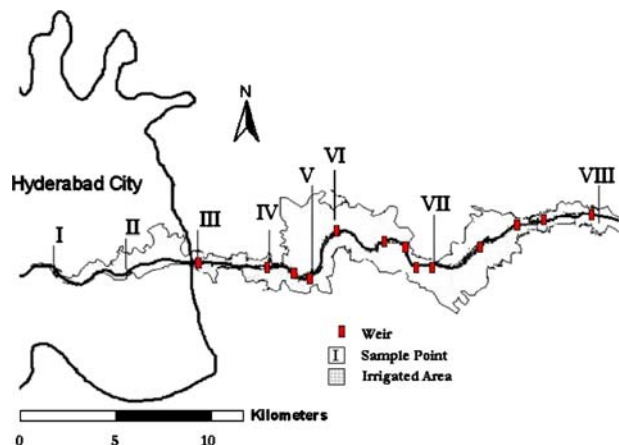
### *Sample point selection*

A 40 km stretch of the river, on which 13 weirs were situated, was selected for the water quality assessment. This stretch of the river was selected as it had no tributaries, nor received major inflows of sewage or surface run-off. Other reasons were accessibility, ease of safe access, travel time and because a very clear water quality improvement was observed. On this stretch eight sample points, approximately 5 km apart from each other were selected, the first of which was situated in the heart of the city (Fig. 1). The selection of sample points was based on the following criteria: reasonable access to the river, the possibility to sample flowing water without having to enter the river, and for the points outside the city, the proximity to a weir. Following a 6 month pilot study, during which sampling and laboratory procedures were tested, a 14 month long water quality survey was undertaken from December 2003 to January 2005.

### *Pathogen and chemical water quality assessment*

River water samples were collected on a fortnightly basis and analysed for Electrical Conductivity (EC), Dissolved Oxygen (DO) and helminth eggs concentrations. A composite grab water sample was collected in a sterile 5 l plastic container and analysed

**Fig. 1** Location of sample points and weirs on the Musi-River in and downstream of Hyderabad



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following the modified Bailenger method (Ayres and Mara 1996) for the presence of helminth eggs. A minimum of three McMaster slides per sample were analysed. Infertile *Ascaris* ova were not included in the *Ascaris* count. DO and EC were measured *in situ*, at 10–20 cm below the water surface, using a hand-held DO and EC meter (Model 85, YSI, Ohio, USA).

Once every 4 weeks additional water samples were collected and analysed for: *E. coli*, biochemical oxygen demand (BOD), and dissolved nitrogen (DN) concentrations. BOD samples were collected in 1.5 litre airtight sterile plastic containers and analysed on a BODTrak™ (HACH, Loveland, USA) using the respirometric method (HACH 1997). DN was obtained by adding nitrate ( $\text{NO}_3^-$ ) and ammonia ( $\text{NH}_4^+$ ) concentrations; nitrate was analysed using Devarda's alloy reduction method while for ammonia the distillation method was used (APHA-WWE-WEF 1998). Samples for *E. coli* enumeration were collected in 500 ml glass bottles and analysed using the membrane filtration technique on the commercial medium m-ColiBlue24®, which allows simultaneous enumeration of total coliforms and *E. coli*. River samples were diluted so that each filter-pad would contain between 20 and 300 colonies. *E. coli* colonies were enumerated and reported as numbers of colonies per 100-ml water sample (APHA-WWE-WEF 1998). All water samples were stored on ice and analysed within 4 h of collection.

### *Flow measurements*

Rough discharge measurements were taken on all sampling days at sample point I. A cross-section of the river was estimated and flow velocity was determined with the help of a float. Flow velocity was determined by timing the movement of a float (i.e., a plastic bottle three-quarters filled with water) over a distance of 25 m. A correction factor of 0.7 was applied to surface velocity to derive a depth-averaged velocity (Shaw 1984). The cross-sectional area of flow was determined from depth measurements made approximately every 1 m across the channel. In addition flow measurements were taken at all irrigation canals with an off-take on the Musi River.

### **Treatment performance**

The hypothesis that different reservoirs on the Musi River acted as a system of WSPs was explored with the help of satellite images and field measurements (area and depth of the different reservoirs), while hydraulic retention time (HRT), volumetric BOD loading and potential treatment performances were calculated using standard WSP design formulae (Mara 1997). Meteorological data were obtained from a local weather station located just outside of the city (ICRISAT, unpublished data).

Poor satellite image resolution allowed for estimates of the surface area of the reservoirs to be made only for the first three weirs on the Musi River. BOD loading on each consecutive reservoir was calculated by using the mean BOD concentrations at the upstream sample point, multiplied by the mean flow in the river. Flows diverted into irrigation canals were deducted from the main flow in the Musi River.

### **Data analysis**

Data analysis was undertaken using STATA 7.0 (STATA-Corporation, College Station, USA). Arithmetic means and standard deviations were calculated for most parameters, with

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the exception of *E. coli* concentrations, for which the geometric mean was calculated. Differences in concentrations between a sample point and the sample point situated directly upstream were compared using a paired, two-sided Student's t-test. A P-value of <0.05 was considered significant. The possibility of a trend between a water quality parameter and the distance from the city was explored using the regression option.

## Results

### Water quality assessment

During the course of the survey 216 water samples were collected on a fortnightly basis and analysed for helminth eggs, EC and DO, while an additional 104 samples were collected on a monthly basis and analysed for *E. coli*, BOD and DN.

### Health indicator parameters

During the course of the survey 143 (66%) water samples from various points were found to be positive for helminth eggs. Three different helminth species were detected; hookworm was the most common, found in 65% of all samples, followed by *Ascaris* (45%) and *Trichuris* (9%). Hookworm and *Ascaris* concentrations were found to be similar at the first two sample points, while *Trichuris* concentrations were found to be much lower (Table 1). Concentrations of all three helminths decreased rapidly after the first weir (sample point III) and decreased further with each additional weir. *Trichuris* eggs were the first to disappear from river water, followed by *Ascaris*, while hookworm eggs were the last to disappear from the river. The *E. coli* concentrations at the first two sample points were high (Table 1) and comparable with those in raw sewage (Mara 1997), though with increasing distance from the city they decreased rapidly.

### BOD, DO, EC and DN

BOD was found to be high at sample points I and II and concentrations showed a similar trend to helminth eggs, with a marked reduction after each weir (Table 2). River water at point VIII was visibly of better quality than that of sample points I and II, reflected in BOD which ranged from 4 to 54 mg/L, with the maximum concentration observed during the period of land preparation. The DO concentrations at the first four sample points were very low, ranging from 0.00–0.71 mg/L (Table 2). The first signs of an improving water quality were observed at sample point VI where DO concentrations ranged from 0.02–3.34 mg/L. Water quality was best at the last sample point with a mean DO concentration of 5.00 mg/L and concentrations ranging from 2.43–8.90 mg/L. EC values remained relatively constant but showed a sharp increase between points VII and VIII. DN showed a weak correlation ( $R^2=0.65$ ) with BOD. DN showed little to no variation for the first four points; only after point V was a decrease in DN observed (Table 2).

### Wastewater flow (Musi discharge)

During the course of the water quality survey the discharge in the Musi River at sample point I varied from: 3.4 m<sup>3</sup>/s to 14.7 m<sup>3</sup>/s. Based on a 24 h survey previously conducted, the total daily river discharge varied from 325,000 m<sup>3</sup>/day in December 2003 to a

**Table 1** Geometric means and 95% confidence intervals (in parentheses) of the health indicator organisms at the different sample points along the Musi-River in and downstream of the city of Hyderabad

Sample point	Distance (km) from Hyderabad <sup>a)</sup>	Total nematodes (eggs/L)	<i>Ascaris</i> (eggs/L)	Hookworm (eggs/L)	<i>Trichuris</i> (eggs/L)	<i>E. coli</i> (CFU/ 100 ml)
I	0	133 (107–165)	61 (46–81)	64 (52–78)	0.9 (0.2–2.0)	$1.4 \times 10^7$ ( $7.4 \times 10^6$ – $2.4 \times 10^7$ )
II	5.2	129 (105–160)	46 (33–65)	69 (55–87)	1.1 (0.3–2.2)	$1.1 \times 10^7$ ( $7.6 \times 10^6$ – $1.6 \times 10^7$ )
III	9.6	24 (20–30)	8.0 (5.0–14)	12 (9.9–17)	0.1 (0.0–0.3)	$3.5 \times 10^6$ ( $2.3 \times 10^6$ – $5.3 \times 10^6$ )
IV	13.9	5.2 (3.7–7.2)	1.1 (0.6–1.9)	3.5 (2.2–5.1)	0.0 (0.0 – 0.1)	$1.7 \times 10^6$ ( $7.5 \times 10^5$ – $3.7 \times 10^6$ )
V	17.3	2.1 (1.3–3.1)	0.1 (0.0–0.3)	1.9 (1.2–2.8)	–	$7.7 \times 10^5$ ( $3.2 \times 10^5$ – $1.8 \times 10^6$ )
VI	20.0	0.8 (0.3–1.5)	–	0.8 (0.3–1.5)	–	$4.1 \times 10^5$ ( $1.6 \times 10^5$ – $1.1 \times 10^6$ )
VII	27.7	0.1 (0.0–0.2)	–	0.1 (0.0–0.2)	–	$2.2 \times 10^4$ ( $7.2 \times 10^3$ – $6.5 \times 10^4$ )
VIII	39.7	–	–	–	–	$7.9 \times 10^2$ ( $3.9 \times 10^2$ – $1.6 \times 10^3$ )

a) Distance measured along the river bed

- Indicates that all collected samples were found to be negative for the presence of ova, values in parentheses are 95% CI

**Table 2** Mean values and 95% confidence intervals (in parentheses) of BOD, DO, EC and DN at the different sample points along the Musi-River in and downstream of the city of Hyderabad

Sample point	Distance (km) from Hyderabad <sup>a)</sup>	BOD (mg/L)	DO (mg/L)	EC (dS/m)	DN (mg/L)
I	0	325 (286–364)	0.10 (0.04–0.16)	1.52 (1.47–1.56)	36.6 (33.2–40.1)
II	5.2	317 (271–362)	0.12 (0.07–0.18)	1.84 (1.78–1.91)	39.1 (36.3–42.0)
III	9.6	162 (135–190)	0.12 (0.06–0.18)	2.03 (1.95–2.11)	38.9 (35.7–42.2)
IV	13.9	95 (75–115)	0.12 (0.06–0.19)	2.00 (1.93–2.07)	38.4 (34.9–41.9)
V	17.3	73 (57–88)	0.22 (0.13–0.33)	1.96 (1.89–2.04)	35.1 (32.0–38.3)
VI	20.0	54 (44–65)	1.12 (0.73–1.51)	1.98 (1.90–2.06)	31.2 (28.5–33.9)
VII	27.7	31 (19–42)	3.03 (2.51–3.56)	1.99 (1.92–2.06)	23.1 (17.9–28.4)
VIII	39.7	15 (8–23)	5.00 (4.36–5.64)	2.26 (2.12–2.39)	10.6 (4.1–17.0)

a) Distance measured along the river bed

maximum discharge of 922,000 m<sup>3</sup>/day in the monsoon month of August 2004. The average discharge was 550,000 m<sup>3</sup>/day. River discharge showed a weak correlation with DO ( $R^2=0.65$ ) and DN ( $R^2=-0.55$ ), with high river discharge associated with high DO concentrations but low DN concentrations.

### Treatment performance

The results show a considerable improvement in water quality from sample point I to VIII for all water quality parameters, with the exception of EC (Table 3). The reduction in helminth egg concentrations from sample point II to III was over 80% and statistically significant for hookworm ( $P<0.001$ ), *Ascaris* ( $P<0.001$ ) and *Trichuris* ( $P=0.01$ ). The trend towards significantly lower egg concentrations after each weir was observed for all weirs for *Ascaris* and hookworm concentrations. The *E. coli* concentrations at sample point VIII were on average over 4 log (or 99.99%) lower than concentrations measured in the city. Unlike for the helminth eggs, *E. coli* concentrations did not decrease significantly across

**Table 3** Treatment performance of the weirs and reservoirs on the Musi-River from sample point I to VIII, in the period December 2003 – January 2005, compared with that of a well designed system of waste stabilization ponds (WSP)

	Treatment efficiency		
	Well designed WSP <sup>a)</sup>	Musi River (sample points: I–VIII)	
		Mean <sup>b)</sup>	Range
Helminths	100%	100%	–
<i>E. coli</i>	99.999%	99.99% (0.03)	99.9–99.999%
BOD	>90%	95% (4)	83–99%
EC		–49% (20)	–91–19%
Nitrogen	70–90	71 (30)	14–100%

a) Source: Mara (1997)

b) Values in parentheses are one standard deviation

any individual weir. However, the logarithm of *E. coli* concentrations (y) did show a significant negative correlation with distance (x in km), which was best captured in a linear trend-line ( $y = -0.11x + 7.57$ ,  $R^2 = 0.86$ ). BOD concentrations after the first weir were on average 46% lower than concentrations found at the sample points located in the city, though the treatment efficiency ( $= (\text{BOD downstream} / \text{BOD upstream}) * 100\%$ ) of the weir showed great variability, ranging from 11% to 69%. The difference in BOD between points II and III, and between all the other upstream and their nearest downstream sample points, was statistically significant ( $P < 0.001$ ). The treatment efficiency for the whole 40 km system was 83% during the period of land preparation (when irrigation canals were closed), but this increased to 93–99% during the remaining months of the year. The reduction in BOD with increased distance (x in km) from the city showed a negative exponential trend with a high statistical significance ( $\text{BOD} = 346.4e^{-0.0838x}$ ,  $R^2 = 0.97$ ). DO concentration across the eight sample points showed a similar but inverse trend to BOD ( $\text{DO} = 0.0573e^{0.117x}$ ,  $R^2 = 0.85$ ). No clear trend was found for EC with increased distance from the city nor was an association found with discharge or other water quality parameters.

## Discussion

For centuries the Musi-River has, through a network of weirs and irrigation canals, provided water to village tanks and fields, thereby supporting fisheries and meeting domestic and agricultural water needs. When the natural flow of the Musi River was obstructed in 1920 following the construction of the two reservoirs upstream of Hyderabad, negative consequences for downstream water users were prevented by planned water releases (Venkateswarlu 1969). This allowed tanks to fill up so that rice could be grown in the months following the rainy season. With the expansion of Hyderabad, the city became increasingly water scarce and water was released from the reservoirs less frequently, while at the same time increasing flows of sewage were discharged into the Musi River bed. Currently the Musi River upstream of Hyderabad is dry, while, as the results of this survey have shown, in and downstream of the city the river flows with essentially untreated domestic wastewater, with corresponding high BOD, *E. coli* and helminth egg concentrations.

Sewage disposal has had a mixed impact on downstream users. The deterioration in water quality means that some tanks close to the city are now unfit for the cultivation of fish and some farmers claim that Musi water is unsuitable for use in agriculture. The deterioration in water quality is however offset by its increased availability and reliability. Since the rapid growth of the city in the 1980's the 'Musi' now flows continuously and this has resulted in the year-round cultivation of rice in the downstream rural areas which in the past was confined to the months following the monsoon season.

### Health implications of Musi-water quality

Public health concern is the most obvious drawback to the use of Musi water in agriculture. The risk of helminth infection has been identified by the WHO as one of the main risks associated with wastewater use in agriculture (WHO 2006). Helminth concentrations in Musi water were typical for domestic sewage in India (Bhaskaran et al. 1956; Lakshminarayana and Abdulappa 1972; Panicker and Krishnamoorthi 1981) but exceeded the water quality standard ( $\leq 1$  egg litre<sup>-1</sup>) set by the WHO for the safe use of river water in agriculture for all but the last sample point (WHO 2006). This was partly corroborated by the findings of an epidemiological study which found an increased risk of hookworm,

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*Ascaris* and *Trichuris* infection in farming families using Musi-water at sample points I and II, though only an increased risk of *Ascaris* infection at sample point III (Ensink 2006; Ensink et al. 2008).

*E. coli* concentrations at sample points I and II were high but decreased rapidly with increased distance from the city, however only at the last sample point, where the geometric mean was 792 faecal coliforms per 100 ml (95% CI: 392–1,601), was a 4 Log reduction achieved, as required by the WHO for the restricted use (cultivation of crops consumed cooked) of irrigation water in agriculture (WHO 2006).

#### Agricultural implications of Musi water quality

Farmers who rely on the Musi River for their irrigation water were unanimous in their opinion that river water quality over the past few decades had deteriorated badly (Buechler and Devi 2003). However their claims regarding the suitability of river water for use in agriculture were more diverse and differed by area and from farmer to farmer. Farmers in the city complained about needles from hospital waste, bottles, plastic bags and other garbage that was found in their fields, but rarely complained about the quality of the water itself. This was most likely because the crop predominantly grown in the city—fodder grass—tolerates high nitrate and salinity concentrations. Farmers in the peri-urban and rural areas were more critical about the water quality, complaining about the regular disposal of chicken slaughter waste into the river and claiming that poor water was responsible for diseases in their cattle and for a 30% reduction in rice yield (Buechler and Devi 2003). However farmers did acknowledge that the nutrient value of Musi water allowed them to save on the cost of chemical fertilizer.

The expansion of the city of Hyderabad has slowly turned peri-urban and rural areas into urban zones and over the last two decades the area between sample points II and V has seen a move from a cropping pattern almost exclusively of rice to a mixture of fodder grass and rice or a complete mono-culture of fodder grass (Buechler and Devi 2003). Poor water quality, and in particular high salinity levels, was mentioned by farmers as an explanation for yield reductions and the shift from rice to fodder grass. However, this shift is not supported by the results of this water quality survey as the salinity threshold for rice ( $3.0 \text{ dS m}^{-1}$ ) was never attained during the period under study (Rhoades et al. 1992) and it is therefore unlikely that salinity alone was responsible for the change in cropping pattern. This was further supported by the cultivation of rice at samples points VII and VIII where no losses in yield were reported. The nitrogen levels in Musi water exceeded recommendations made by the FAO for unrestricted irrigation (Pescod 1992), though guideline values were only occasionally exceeded and only by a small margin. In contrast, similar nitrogen concentrations in trials in Korea even resulted in a 10% increase in rice yield (Yoon et al. 2001). Concentrations of metals in Musi water were in general low (IWMI, unpublished data) with the exception of iron (Fe) and aluminium (Al) though even these did not exceed agricultural guideline concentrations (Pescod 1992), or guideline concentrations set to protect public health (WHO 2006).

The shift from rice to fodder grass cultivation might have had reasons other than water quality alone, though a shift from rice to a less sensitive crop, like fodder grass, is more than plausible. The growth of the city and with it the increased need for skilled and unskilled labour might also have prompted a change from a labour intensive crop, like rice, to a less labour intensive crop like para grass. This, combined with a rapid growth in the demand for milk and dairy products in India (Delgado et al. 1999; Kurien 2004), has resulted in a situation where a profitable living can be made by growing fodder grass for

local dairy producers. Reductions in rice yields could possibly be explained by the exhaustion of an originally deficient and poor soil, by the double rice cropping system which is practised now and the generally held perception by farmers that if Musi water is applied, there is no longer a need to apply chemical fertilizer. These speculations are, however, beyond the scope of this water quality survey, which was not set up with the intention of investigating why rice yields have gone down, nor to explore why farmers shifted from one crop to another. The results of this survey alone are therefore unable to answer these questions but they provide some evidence that factors other than water quality, such as local livelihood strategies, land prices, distance to local markets and soil quality, may have played a role in changing agricultural practices, and that further investigation would be required to confirm the reasons.

### Wastewater quality remediation

The results of the survey showed an impressive improvement in water quality from sample point I to VIII, especially considering the relatively short distance of 40 km. These improvements are probably the result of a set of different remediation processes: principally sedimentation, dilution, aeration, natural die-off and exposure to UV-light. These processes made the weirs on the Musi River rival the treatment performance of well-designed WSP systems (Table 3), the recommended method for wastewater treatment in arid and semi-arid developing countries (Mara 1997).

Past studies in Mexico and Israel have shown that weirs and reservoirs help promote sedimentation and water quality improvements (Blumenthal et al. 2001; Juanico and Shelef 1991). Sedimentation behind the first and subsequent weirs on the Musi has played an important role in the reduction of BOD and helminth concentrations. This was confirmed by sediment analysis at the first weir which showed very high concentrations of helminth eggs, ranging from 67,000 to 734,000 ova  $\text{kg}^{-1}$  of sediment (Hofstedt 2005). In addition to sedimentation, anaerobic digestion taking place in the reservoirs created by the weirs might have played an important role in water quality improvement. The BOD loading in the reservoirs behind the first two weirs was estimated (Table 4) to range from 110 to 160  $\text{kg m}^{-3} \text{d}^{-1}$ , which is above the minimum volumetric loading (100  $\text{kg m}^{-3} \text{d}^{-1}$ ) to maintain anaerobic conditions (Mara 1997). In the third reservoir, at sample point V, the volumetric loading was estimated to be 90  $\text{kg m}^{-3} \text{d}^{-1}$  and here aerobic conditions returned to the river. This was confirmed by the first improvements in DO-concentrations at sample point V. Based on this the first two reservoirs on the Musi River can be considered as anaerobic ponds and the following reservoirs facultative and maturation ponds. Treatment performance in the first two reservoirs can thus be calculated based on the minimum temperature during the coldest month (January 2004), which was 21°C. This would have

**Table 4** Estimated reservoir volume, hydraulic retention time (HRT) and volumetric BOD loading for the first three reservoirs on the Musi-River

Sample point	Reservoir size ( $\text{m}^3$ )	HRT (h)		BOD loading ( $\text{kg ha}^{-1} \text{d}^{-1}$ )
		Mean	Range	
III	1,100,000	48	29–81	159
IV	410,000	29	14–90	115
V	260,000	21	9–96	90

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resulted in (minimum) BOD removal efficiency of 62%. In fact, the mean BOD removal efficiency was approximately 40% for each individual weir/reservoir, but for the first two reservoirs combined it was 70%, which was close to the maximum removal performance that anaerobic ponds can achieve under ideal conditions (Mara 1997).

The sedimentation of organic matter and other suspended material will over time reduce reservoir capacity, hydraulic retention and thus a reservoir's treatment ability. There is potential for these reservoirs to be cleaned out naturally during the monsoon season, when peak river discharges may re-entrain settled solids. This would be beneficial as it would maintain the treatment capacity of the reservoirs, though the high *Ascaris* egg concentrations in the sediment and their possible re-suspension during peak flow events could be of concern, as *Ascaris* eggs have been reported to remain viable for up to 2.5 years in sludge (Ayres et al. 1993). However, the direct health impact on farmers can be expected to remain limited during the monsoon season as a result of dilution by rain water and the lower irrigation water demand that results in decreased contact with wastewater arising from irrigation operations. *E. coli* removal has been associated with the sedimentation of organic matter (Feachem et al. 1983), though settling velocities for *E. coli*, because of lower weight, are much lower than those of helminth eggs. *E. coli* concentrations showed a strong association with distance and this suggests that the predominant mechanism for the removal of *E. coli* from Musi water was probably natural die-off with time, though dilution as a result of groundwater return flows from irrigated fields, and exposure to UV light have certainly played a role too. However, the impact of UV light at the first six sample points has probably been minimal, as a consequence of the high turbidity which prevents effective penetration of UV light into the water column (Otaki et al. 2003). Recontamination of Musi-water with *E. coli* downstream of irrigation weirs should be considered, and would suggest and even higher treatment performance as currently reported, as the river is frequently used by water buffaloes for bathing and drinking.

The average salinity increased by almost 50% from sample point I to sample point VIII. This increase came partly as a result of an inflow of more saline wastewater within the city's boundaries while an additional increase in salinity levels occurred between sample points VII and VIII in the rural stretch of the river where no wastewater was discharged. Only evaporation and inflow of water with a higher salinity could have resulted in this increase because salinity is a conservative parameter. The increase in salinity from 2.0 dS m<sup>-1</sup> to 2.3 dS m<sup>-1</sup> cannot be explained by evaporation alone and the most likely explanation is the inflow of saline drainage water from irrigated fields. Soil irrigated with wastewater were observed to roughly accumulated 34 kg/ha/year (McCartney et al. 2008).

### Environmental impact

On a first visit to the Musi River in the heart of the city one might easily conclude that the growth of the city and the consequent large-scale disposal of wastewater into the river has been an ecological disaster. Yet the river had long been dry, and one could argue that large scale wastewater disposal has given the river a new life. The origin of the wastewater is largely domestic and DO concentrations improved rapidly after 17 km. A benthic survey along the river found that habitat conditions for macro-invertebrates improved rapidly, and consequently greater taxa richness was found with increasing distance from the city. This led to a greater diversity in the general bird population and in particular of water-fowl using the river (IWMI, unpublished data). This, combined with clearly visible and measured improvements in water quality, gave the impression that 40 km downstream of the city there was a normal river ecology situated in an agricultural setting.

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## Conclusion

The city of Hyderabad disposed of very large quantities of untreated domestic sewage into the dry bed of the Musi River. Sewage disposal had a mixed impact on downstream users. Poor water quality had a negative impact on farmer health and possibly crop productivity, though increased reliability and availability of irrigation water also had a positive impact on local livelihoods. For most of the farmers, agriculture is their sole livelihood; to ban the use of Musi River for irrigation would be highly undesirable. The eventual aim should be the treatment of wastewater before it is used in agriculture in and around Hyderabad. However in the mean time additional health protection measures like regular treatment programmes with anthelmintic medication and improvements in local water supply and sanitation should be implemented.

The natural remediation efficiency of the river system aided by the construction of irrigation infrastructure, particularly weirs, was high and comparable to the treatment efficiency of a well designed waste stabilization pond system. Hyderabad municipal council intends to invest large amount of money into wastewater treatment technology. The processes currently taking place in the Musi River could be taken into consideration before large scale investments are undertaken in wastewater treatment technology in Hyderabad, as complementary technology could save money and land in the city.

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