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Wastewater use in Agriculture in Andhra Pradesh, India

An evaluation of irrigation water quality in reference to associated health risks

Charlotta Hofstedt

ABSTRACT

Wastewater use in Agriculture in Andhra Pradesh, India. An evaluation of irrigation water quality in reference to associated health risks and agricultural suitability.

Charlotta Hofstedt

The use of untreated domestic sewage in agriculture is a growing practice in many parts of the world. It is being looked upon as a valuable and reliable resource in water scarce communities. Wastewater is usually rich in nutrients and the use results in high yields without the need for artificial fertilisers. But with the use of untreated wastewater follows a number of associated health risks, e.g. a higher prevalence of helminth infections has been seen among wastewater users compared to non-users. This water quality study was performed along the River Musi in Andhra Pradesh, India. The Musi River flows through the city of Hyderabad carrying the most of the town's wastewater. Downstream of Hyderabad the wastewater is used by farmers for irrigation. Along the river weirs are constructed which diverts the irrigation water into canals and reservoirs are formed where the flow velocity slows down. The study area stretches from Hyderabad and 28.7 km downstream. The hypothesis was that the existing irrigation infrastructure acts like Wastewater Stabilisation Ponds and the aim was to quantify the impact of the weirs on water quality and to evaluate the irrigation water quality in reference to associated health risks and agricultural suitability. Within the study area the BOD, *E coli* and Nematode removals were 86.9%, 99.9% and 99.9% respectively. Despite the high removal the *E coli* and Nematodes, the concentrations exceed WHO guidelines for unrestricted and restricted irrigation, and there exists an excess risk of intestinal nematode- and enteric infections for farmers. Dissolved oxygen and salinity increases downstream and due to the high salinity farmers could experience reduced crop yields. By looking at removal patterns, and the change in water quality parameters, the conclusion can be made that the reservoirs act like anaerobic ponds in a Wastewater Stabilisation Pond system.

Keywords: India, Wastewater Irrigation, Health, Parasites, Sanitation, Wastewater Treatment, WHO, Water Quality, River Pollution.

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REFERAT

Användning av avloppsvatten för bevattning i Andhra Pradesh, Indien. En utvärdering av bevattningsvattnets lämplighet med hänsyn till hälsorisker och jordbruk.

Charlotta Hofstedt

Användandet av obehandlat avloppsvatten inom jordbruket är en växande företeelse i många delar av världen. Speciellt i vattenfattiga områden där avloppsvattnet ses som en värdefull och pålitlig resurs. Det höga näringsinnehållet minskar behovet av konstgödsel och detta ökar böndernas inkomster. Men med användandet av avloppsvattnet följer vissa hälsorisker. Bland annat har man sett en högre förekomst av inälvsmaskar hos bönder som använder orenat avloppsvatten jämfört med de som använder rent vatten. Den här vattenkvalitetstudien har utförts längs floden Musi i Andhra Pradesh, Indien. Musi rinner igenom staden Hyderabad och mycket av stadens avloppsvatten dumpas i floden. Nedströms Hyderabad används detta vatten för bevattning. Längs med floden är dammar byggda, för att avleda vattnet i bevattningskanaler. Reservoirer bildas då flödeshastigheten minskar. Studieområdet sträcker sig från Hyderabad och 28.7 km nedströms. Hypotesen var att reservoirerna fungerar som biodammar och syftet var att kvantifiera dammarnas inverkan på vattenkvaliteten och utvärdera dess lämplighet utifrån ett hälso- och jordbruksperspektiv. Inom studieområdet är reningen med avseende på BOD, Nematoder och *E coli* 86,9%, 99,9% respektive 99,9%. Trots att reningen är så hög överstiger Nematod- och *E coli*-koncentrationerna Världshälsoorganisationens riktlinjer och utgör en hälsorisk för bönder och konsumenter. Syre- och salthalt ökar nedströms och den höga salthalten kan ha negativ inverkan på jordbrukets avkastning. Genom att titta på reningsmönster och förändring av olika vattenkvalitetsparametrar är en av slutsatserna av detta arbete att reningen i dammarna motsvarar den rening som sker i de anaeroba bassängerna i ett biodammsystem.

Nyckelord: Indien, Avloppsvatten, Bevattning, Hälsa, Parasiter, Sanitet, Avloppsrening, WHO, Vattenkvalitet, Förorening.

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LIST OF ABBRIVIATIONS

BOD	Biochemical Oxygen Demand (mg/l)
COD	Chemical Oxygen Demand (mg/l)
DO	Dissolved Oxygen (mg/l)
EC	Electrical Conductivity (dS/m)
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IWMI	International Water Management Institute
PCB	Pollution Control Board
SAR	Sodium Adsorption Ratio
TDS	Total Dissolved Solids (mg/l)
UASB	Upflow Anaerobic Sludge Blanket
USAID	United States Agency for International Development
USEPA	United States Environmental Protection Agency
WHO	World Health Organisation
WSP	Wastewater Stabilisation Pond

1 INTRODUCTION

In many countries with a shortage of water there is also an escalating growth in population, resulting in increasing demand for drinking and agricultural water. Along with the increase in water demand, comes the production of vast amounts of wastewater, both industrial and domestic. With the rapid urbanisation the municipalities have no means to manage the wastewater produced, resulting in inadequate or nonexistent treatment. The disposal of wastewater into water bodies imposes a public health risk. The pollution of fresh water sources further contributes to the water shortages. A recent report from the World Health Organisation says that nearly 20% of the world's population have no source of safe drinking water (Bartam *et al.*, 2005). International Water Management Institute estimates that by 2025 1.8 billion people will live in regions with absolute water scarcity (IWMI, 2000).

In water scarce communities wastewater is looked upon as a valuable resource with its high nutrient content and its year around availability. In many developing countries the urbanisation will continue and as a result the wastewater flows will increase in the future. The use of untreated wastewater is a growing practice that is difficult to control. There exist many negatives effects of the use, e.g. health hazards due to microbial and chemical contamination, soil salinisation and contamination of groundwater sources. But many times the economical benefits are much larger and farmers experience larger crop yields without the expenses of fertilisers.

With the fact that poor water supplies and poor sanitation is the second largest cause of death (Murray *et al.*, 1996) one realise the need for improving sewage collection and treatment before discharging it to the recipient. But as the treatment capacity already lag behind it would require huge investments for already cash tied communities. Now when the wastewater irrigation is a fact the focus is on making the use as safe as possible for farm workers and for consumers of wastewater irrigated crops.

2 OBJECTIVES

This Master thesis was done within the scope of an ongoing project at the International Water Management Institute (IWMI) and the London School of Hygiene and Tropical Medicine. In the past, studies have been made showing there exists an excess risk of health problems among untreated wastewater users compared to fresh water and treated wastewater users. Little is known about how the concentration of nematodes influence the health risk and the aim of the IWMI project is to investigate the relationship between the concentration of intestinal nematode eggs in river water and hookworm infections and ascariasis in exposed farmers (Ensink, 2003).

The irrigation infrastructure with diversion weirs and canals affect the hydraulic regime of a river as flow velocities go down, resulting in sedimentation of suspended particles. The hypothesis of this Master thesis is that the reservoirs, formed by diversion weirs, act like wastewater stabilisation ponds and therefore improve the water quality downstream. The objectives were to

- quantify the impact of irrigation infrastructure on water quality;
- describe and explain the dynamics that cause the change in water quality along the river;
- evaluate agricultural suitability of the river water;
- evaluate water quality from a health risk perspective.

3 BACKGROUND

3.1 WASTEWATER IRRIGATION

The practice of irrigation with wastewater is old and worldwide. Already in the late 1800s and early 1900s there existed sewage farms throughout Europe, Australia, Latin America and the USA. In the outskirts of Paris, 5300 ha of land were sewage-irrigated land and in Berlin, 17200 ha (Shuval *et al.*, 1986). The interest during that era was mainly due to the ambition to keep the rivers free from faecal contamination. With technical development, better treatment systems and an increasing awareness of the importance of microbes in disease transmission, wastewater irrigation fell out of fashion. After World War II, the practice once again gained attention, not only to prevent river pollution, but also as a way to come to terms with the worlds increasing water demand (Shuval *et al.*, 1986).

Today much effort is made to make use of wastewater and it is looked upon as a valuable resource. A World Bank report in 1985 estimated that over 80 % of the wastewater flow in urban areas in developing countries is used for agricultural purposes (Gunnerson *et al.,* 1985). But wastewater irrigation is practiced in developed countries as well. In Israel, wastewater irrigation is controlled and carefully planned. 65 % of the total domestic sewage is reused. The wastewater is treated and stored during the wet season and used for agricultural purposes during the dry summer season (Friedler, 2001). Wastewater reuse may also, as in many parts of India, and

Pakistan (van der Hoek *et al*., 2002), be indirect, that is, wastewater is disposed into rivers and the contaminated river water is used for irrigation. The growing cities cannot handle the sewage produced and it is disposed in to water bodies. Four billion people lack wastewater treatment (Mara, 2001), thus large amounts of sewage is disposed in to water bodies. The untreated urban wastewater is used downstream for uncontrolled, unrestricted irrigation. The authorities do not have the financially means, or simply neglect, to control the practice of wastewater irrigation.

Wastewater use in agriculture has increased over the past two decades. Several factors influence the development in this direction. The increasing scarcity of alternative waters for irrigation; high cost of artificial fertilisers and advanced treatment plants; sociocultural acceptance of the practice and the demonstration that health risks and soil damage is minimal if necessary precautions are taken (Blumenthal, 2000).

3.2 HEALTH RISKS

By identifying the factors[1] that contribute to the transmission of pathogens by raw wastewater irrigation, in developing countries, Shuval et al. (1986) ranked the pathogens and their associated health risks in the following descending order:

1. Helminths. The intestinal nematodes constitute a risk to agricultural workers and to consumers of wastewater irrigated produce

2. Bacteria and protozoa. The transmission of dysentery, cholera, typhoid and other bacterial and amoebic diseases to consumers of wastewater irrigated produce

3. Viruses. The transmission of viral infections to agricultural workers or to those living close to wastewater irrigated fields

Depending on the origin of the wastewater, it may contain different amounts of toxicants (non-organic or organic) as heavy metals and pesticides. These might also be a health risk to workers and consumers. A study in India (Singh *et al.*, 2004) reports higher levels of toxicants in urine and blood in a population living in an area irrigated with treated/untreated wastewater compared to people in a control area. The daily intake was 2-4 times higher in the exposed area. A significant difference in neurobehavioral functions was reported.

3.2.1 Helminths

Helminth is a worm that is parasitic on the intestine of vertebrates. Roundworms, tapeworms and flukes are all helminths. The soil-transmitted helminths are the most common and the most critical to human health. *Ascaris lumbricoides*, *Necator americanus* and *Ancylostoma duedenale* and *Trichuris trichuria* are all helminths belonging to the phylum[2] Nematoda (Bogitsh, 1998).

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[1] The factors considered where: 1.Persistence in the environment. 2.Infective dose 3 Immunity 4. Transmission routes (food, water, hygiene) 5. The need for a soil development stage.

[2] A primary division of a kingdom, as of the animal kingdom, ranking next above a class in size

According to WHO, 2 billion people suffer from soil-transmitted helminths whence 800 million are school age children. 135 000 people every year are estimated to die due to helminth infections.

Ascaris lumbricoides is a large intestinal roundworm. The female can measure 40 cm and the male 30 cm. The female can produce up to 200 000 eggs per day. The eggs measure 45-75 µm by 35-50 µm (Figure 1).

Figure 1 An egg of *Ascaris lumbricoides* as seen under the microscope. Picture from www.who.org

The adult worm inhabits the small intestine, there it draws nourishment from the semidigested food, and at this site copulation occurs. The eggs pass with host faeces. To develop, the eggs require moist soil. They are resistant to desiccation but sensitive to soil temperature. The fertilised eggs develop at temperatures around 25 ºC but cannot survive above 38 ºC, and under 15.5 ºC the development ceases. It takes 2-4 weeks in soil to develop the infective larva, and infective eggs may remain viable in the soil for 2 years or longer. The egg enters the host through dirty fingers or contaminated foods. An infective egg hatches in the duodenum and from there the larva enters the circulatory system, via the liver and the heart, to the lungs. In the pulmonary capillaries the larva moults twice before it migrates to the alveoli. The host will cough and swallow the larva and in that way it will again reach the small intestine where it will moult further and become sexually mature. This journey, from the ingestion of an infective egg to adult worm, takes about 3 months (Figure 2).

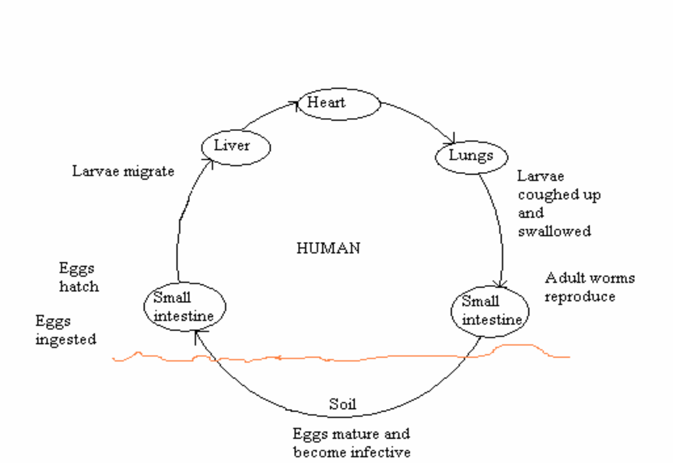

Figure 2 Schematic drawing of the life cycle of *Ascaris lumbricoides.* Source: Bogitsh B.J., 1998. Human Parasitology.

The symptoms are upper abdominal discomfort and allergic reactions (asthma, insomnia, eye pain and rashes) to metabolic excretions of adult worms and dead or dying worms. Both larva and adult worms can migrate and cause damage to surrounding organs. Mechanical blockage of the intestine is also occurring. Loss of appetite and insufficient absorption of nutrients is a result of heavy infections. Enteritis and obstruction symptoms may occur. The passage of the larva through the lungs may cause a fever (Iwarson, 1991). 1 billion people suffer from Ascaris infection, which is prevalent in children. In 1990, 62 million people suffered from high intensity infections (Murray *et al.,* 1996). In Asia, 40% of the population are believed to be infected with Ascaris (Bogitsh *et al.,* 1998).

Necator americanus and *Ancylostoma duedenale* are two species of **hookworm** that cause infection in humans. *A. duodenale* is considered the more pathogenic of the two. Females measure about 9-13 mm and the males 5-11 mm. The eggs are 64-76 µm by 36-40 µm (Figure 3).

Figure 3 A hookworm egg as seen under the microscope. Picture from www.who.org

A. duodenale uses almost exclusively humans as hosts, but *N. americanus* also uses dogs. They inhabit the small intestine in their host, were they feed on blood from the intestine wall. The eggs pass with host faeces, and when disposed in soil it hatches after 1-2 days. The hookworm egg requires a temperature of 23 – 33 ºC, shade, and sandy soil rich in organic materials. After 3 to 6 weeks (Iwarson, 1991) of different stages of development, the hookworm is ready to penetrate the skin of the host. The larva can survive for up to 6 weeks in the upper soil layer (Bogitsh *et al.*, 1998). After penetration it enters the lymphatic system and travels through the right side of the heart to the lungs from where it is coughed up and swallowed. Whilst in the small intestine, they undergo their last transformations before becoming sexually mature. The time from penetration of the host skin to adulthood is 5-6 weeks (Figure 4).

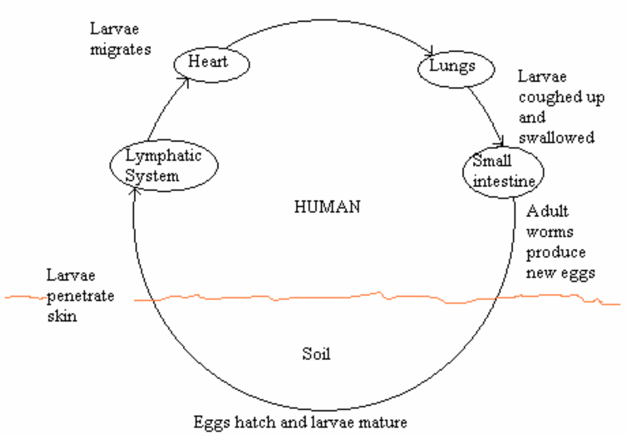

Figure 4 Schematic drawing of the life cycle of hookworms. Source: Bogitsh B.J., 1998. Human Parasitology.

A local irritation called ground itch may occur when the larva penetrates the skin. Severe bleeding is sometimes seen when a large amount of larva leaves the lungs, otherwise a dry cough is the only symptom at this stage. The most serious stage of infection is when the adult worm begins feeding on blood. The hookworm causes a blood loss of 0.15 ml per worm and day (Alestig). A massive infection can cause a blood loss of 100 ml per day (Iwarson, 1991), which may result in severe anaemia, protein deficiency, dry skin and hair, oedema, stunted growth, delayed puberty, mental dullness and even death. Over 450 million people are infected with hookworms (Iwarson, 1991). It is estimated that in 1990, 152 million peopled suffered from high-intensity hookworm infection. 36 million also suffered from anaemia due to the infection (Murray *et al.,* 1996).

Trichuris trichuria is also known as whipworm because of its whip-like appearance. The female measures 30-50 mm and the male is somewhat smaller. The female deposits up to 5000 eggs per day and the eggs measure 50 µm by 22 µm (Figure 5).

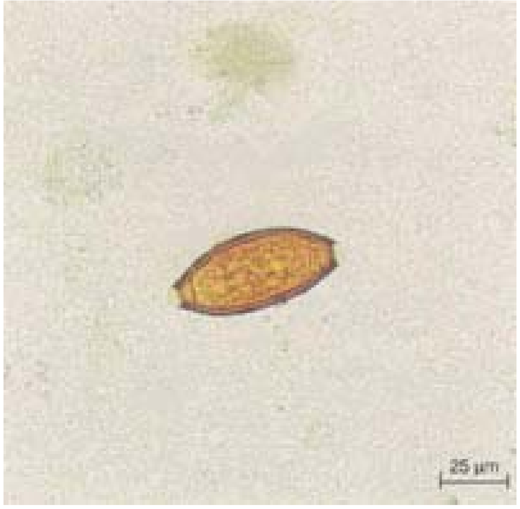

Figure 5 An egg of *Trichuris trichuria* as seen under the microscope. Picture from www.who.org

The whipworm mainly inhabits the human colon, but is also found in appendix and rectum. Eggs pass with host faeces and when disposed in warm, moist soil an infective stage is developed after 3-6 weeks. The human become infected when ingesting contaminated foods or water. The eggs hatch in the upper parts of the small intestine where they mature before migrating to the colon where they develop to sexual maturity. The adult worms are embedded in the colon mucous membrane, where they can survive for approximately 2 years. The time from ingestion to adult stage is 30-90 days (Figure 6).

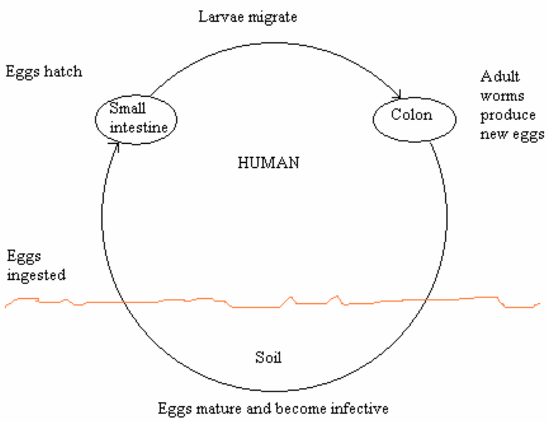

Figure 6 Schematic drawing of the life cycle of *Trichuris trichuria.* Source: Bogitsh B.J., 1998. Human Parasitology.

Chronic infections have symptoms as bloody stools, abdominal pain, weight loss, rectal prolapse, nausea and anaemia. The anaemia is due to bleeding when the worms penetrate the intestinal wall. Several hundred million people are infected by *Trichuris trichuria* (Bogitsh 1998). 45 million suffered (in 1990) from high-intensity infections (Murray, 1996).

3.2.2 Bacteria

A wide range of bacteria exists in domestic wastewater. This is not surprising when one considers that there exist 10^{10} to 10^{12} bacteria per gram of human faeces (Iwarson, 1991). The concentration of pathogenic bacteria and viruses in the faeces of an infected person ranges from 10^{6} to 10^{8} organisms per gram faeces (Shuval *et al.*, 1986). A large group is the faecal coliforms, also known as Enterobacteriaceae, which refers to a group of enteric gram-negative rods. Many of the coliforms are part of the normal flora in the intestine, e.g. *Escherichia coli (E.coli)* (the most common) and species of the genera *Klebsiella*, *Enterbacter* and *Proteus*. Others, e.g. *Salmonella* and *Shigella*, are pathogenic to humans. The normal flora bacteria do not generally cause disease, as long as they do not reach sites other than their normal. Common are urinary tract infection, sepsis and meningitides. Some strains of *E coli* may also cause enteric illness, e.g. Enterotoxogenic (ETEC) and Enteropathogenic *E coli* (EPEC) (Jawetz *et al.*, 1991).

Other pathogenic gram-negative rods (not belonging to the Enterobacteriaceae) found in wastewater, are *Vibrio cholerae*, *Campylobacter jejuni* and *Yersinia entercolitica*.

A cholera outbreak occurred in Jerusalem in 1970. It could be related back to wastewater-irrigated fields (Fattal *et al.*, 1986). Studies in Chile suggest that typhoid fever (caused by *Salmonella typhi*) can be transmitted through crops irrigated with raw wastewater (Shuval *et al.* 1986).

The persistence of bacteria in water, wastewater, soil and crops varies from a couple of days (*Campylocbacter* spp) to 3 months (Salmonella spp and EPEC). The bacterial die off is dependent on time, temperature (Feachem *et al.*, 1983), pH, light intensity and dissolved oxygen. If a crop is contaminated with pathogenic bacteria, many of the bacteria would die before reaching the consumer, but the infective dose is very small for some bacteria; e.g. 10^{3} for *Shigella* (Jawetz *et al.*, 1991).

Feacal coliform counts per ml water are used as an indicator of the overall microbial quality of a wastewater and to determine the risk of possible presence of pathogenic organisms.

3.2.3 Viruses

The most commonly detected pathogenic viruses belong to the enterovirus group, which includes the poliovirus. Other viruses mainly cause gastroenteritis and diarrhoea. Hepatitis A is also commonly found in wastewater.

No evidence exist to prove that viruses causes an excess risk for consumers and wastewater workers, but as viruses may live on crops for as long as 60 days (Feachem *et al.*, 1983), and the infective dose usually is low, outbreaks could occur in non-endemic areas. 1955-56 in Sweden, over 600 people took ill with Hepatitis A infection. The reason was oysters that had been stored in the sea close to a sewage outlet (Iwarson, 1991).

3.2.4 Protozoa

Protozoa are eukaryotic single cell (or colonial) organisms. Many are capable of forming cysts[3]. *Entamoeba histolytica* (an amoeba) and *Giardia intestinalis* (a flagellate, formally known as *Giardia lamblia*) have this ability and form cysts in the intestine of the infective host. The cysts are expelled with faeces. The cysts protect the protozoa from environmental effects and from the acid fluid in the gastric tract of the host. (Bogitsh *et al.*, 1998) The *Entamoeba histolytica* cysts can survive up to 10 days on crops (normally 2 days) and up to 20 days in soil (normally 10 days) (Feachem *et al.*, 1983).

Entamoeba histolytica is the causative agent of amoebic dysentery and *Giardia intestinalis* causes severe diarrhoea.

3.3 WHO GUIDELINES

The first meeting on wastewater use in agriculture was held by World Health Organisation, WHO, in 1970 and led to the first guidelines, published in 1971. In 1985 WHO, the World Bank and the International Reference Centre for Waste Disposal arranged a conference in Engelberg, Switzerland, to discuss the then applied hygiene standards which were considered too strict. The Engelberg report proposed a more realistic approach and the recommendations resulted in the WHO guidelines for wastewater reuse, published in 1989.

Microbiological qualities recommended for treated wastewater for use in agriculture are:

> ≤ 1 viable intestinal nematode egg per litre water for restricted and unrestricted irrigation;
>
> $\leq 10^3$ faecal coliform bacteria per 100 ml for unrestricted irrigation.

Restricted irrigation refers to irrigation of trees, fodder and industrial crops, fruit trees and pasture and **unrestricted irrigation** to irrigation of edible crops, sport fields and public parks (WHO, 1989).

Irrigation with wastewater result in a potential risk for both farm workers and consumers, depending on what crops are grown and how the irrigation is performed. The strictest guidelines (≤ 1 egg/l and ≤ 1000 faecal coliforms/100ml) is applied when unrestricted irrigation is performed and a wide range of people are affected by the wastewater, i.e. farm workers, consumers and the general public. A more stringent guideline of 200 faecal coliform/100 ml, is recommended for irrigation of public lawns. With restricted irrigation only workers are affected, as the crops are unlikely to be eaten raw by humans. In this case no guideline is specified concerning faecal coliforms but the nematode value is the same as for unrestricted irrigation. A third category refers to **localised irrigation** of trees, fodder and industrial crops, fruit trees and pasture, but without human exposure. No guidelines are set in this category (WHO, 1989).

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[3] Cyst: A small capsule-like sack that encloses certain organisms in their dormant or larva stage

New epidemiological studies have been performed since, and new guidelines are under revision. After reviewing the current epidemiological evidence, Blumenthal *et al.* (2000) suggest, the following microbiological quality:

> ≤ 0.1 viable intestinal nematode egg per litre for unrestricted irrigation (in cold climate or if surface irrigation is used) and for restricted irrigation (if children under 15 are exposed, either by work or play)
>
> ≤ 1 viable intestinal nematode egg per litre for unrestricted irrigation (in hot and dry climates and if surface irrigation not used) and for restricted irrigation (no children under 15 are exposed)
>
> ≤ 10^3 faecal coliform bacteria per 100 ml for unrestricted irrigation and for restricted irrigation (if children under 15 are exposed, either by work or play or if furrow/flood irrigation is used)
>
> ≤ 10^5 faecal coliform bacteria per 100 ml for restricted irrigation (no with exposure to children and if spray/sprinkler irrigation is used)

For unrestricted irrigation, Blumenthal *et al.* (2000) suggest a stricter guideline of ≤ 0.1 eggs per litre in conditions that favour the survival of helminth eggs (lower temperature or surface irrigation). The less strict guideline would apply for hot weather conditions, if surface irrigation is not practiced, and where crops with short shelf life are grown. The faecal coliform guideline (10^3/100 ml) is kept as no further evidence exists that support a change. It may, however, be necessary to make it more stringent in climates with heavy rainfalls during growing season, due to risk of recontamination of crops in uncovered plots. A more stringent guideline limit, of ≤ 200 FC/100 ml, is recommended in irrigation of public lawns, with which the public may come in direct contact.

For restricted irrigation a faecal coliform guideline, of ≤ 10^5 faecal coliforms per 100 ml is introduced. The review by Blumenthal *et al.* (2000) indicate that new evidence shows a risk of enteric infections in farming families in direct contact with treated wastewater (Mexico) and in communities near fields sprinkler irrigated with more than 10^6 faecal coliform per 100 ml (USA). The guideline is reduced if flood or furrow irrigation is used and if children below 15 are exposed, either by play or work, with treated wastewater, as evidence show an excess risk of enteric infections in those cases. As for intestinal nematodes, studies (Mexico) suggest that as long as children are exposed, the stricter guideline at ≤ 0.1 egg/l should be applied.

In 1992, the United States Environmental Protection Agency (USEPA) and the USAID developed their own guideline for wastewater reuse. The USEPA guidelines are far stricter than the WHO guideline. The criteria are that there should be no excess risk by using (treated) wastewater. For irrigation of crops likely to be eaten raw, no detectable faecal coliforms/100 ml is allowed, and for restricted irrigation the guideline is ≤ 200 faecal coliforms/100 ml. No nematode egg guideline is specified. USEPA also specifies guidelines on other water quality parameters. For unrestricted irrigation (food crops, including crops eaten raw) BOD values should not exceed 10 mg/l; for restricted irrigation the BOD threshold value is 30 mg/l. A value for suspended solids (SS), at 30 mg/l, is also specified.

Fattal *et al.* (2004) estimated that the global annual risk of contracting infectious diseases (typhoid fever, rotavirus infection, cholera and hepatitis A) from eating raw vegetables irrigated with untreated wastewater is in the range of 5-15%. If wastewater was treated to meet the WHO standards for unrestricted irrigation, the risk diminished to 0.0001%. The treatment cost per case prevented is estimated to US$125. If one were to treat wastewater to meet the USEPA standard, the cost would be US$450,000 per case prevented.

3.4 WATER QUALITY PARAMETERS

There are many ways to describe the quality of water. Depending on how the water is used and what you are looking for, different parameters are important. Here follows a short description of the parameters used in this work.

pH is an indicator of the acidity or basicity of a water. The normal pH range for irrigation water is 6.5 to 8.4. The pH is seldom a problem in itself. The main reason for pH measuring is to detect abnormal water, which may contain toxic ions or cause a nutritional imbalance (Ayers *et al.*, 1985) The pH value is also important for aquatic fauna but waters with pH between 6 and 9 are not likely to be harmful to fish (Davie, 2003).

Electrical conductivity, **EC**, is used to estimate the amount of ions dissolved (water salinity). It measures the ability of a water sample to transmit electrical current, which is proportional to the ion content. The electrical conductivity is usually expressed as deciSiemens/meter (dS/m). Total Dissolved Solids, **TDS**, is another measure of salinity. It shows the amount of dissolved substances in the water, both ions and uncharged molecules. TDS is directly proportional to EC and expressed as a concentration mg/l. The amount of dissolved salts in soil water is determined by the amount of dissolved salts in the irrigation water. In soil water with high salinity, the osmotic pressure increases and the plants use more energy to take up water. This results in an increase in respiration and a decrease of plant growth and yield (Pescod, 1992).

The oxygen content of water can be expressed either as mg /l dissolved oxygen, **DO**, or percentage saturation. The water's ability to dissolve oxygen is temperature dependent. Dissolved oxygen is vital to the aquatic fauna, and many species of fish require DO contents above 5 mg/l, whereas coarse fish can survive in 2 mg/l (Davie, 2003). The oxygen is also used by bacteria to break down organic matter and thus anaerobic conditions can be found when the organic content is high (as in domestic sewage). When the dissolved oxygen is depleted the water becomes anaerobic and sometimes highly reducing (Hounslow, 1995).

The biochemical oxygen demand, **BOD**, is a measure of how much biodegradable organic matter a water sample contains but it is the amount of oxygen required to break down the organic matter in the sample that is measured. Usually this is measured during 5 days. The BOD is expressed as mg/l. The more oxygen required the more organic matter. Organic substances present in sewage are carbohydrates, lignin, fats, soaps, synthetic detergents, proteins and organic chemicals from process industries (Pescod, 1992). A normal stream should have values of less than 5 mg/l and untreated sewage is normally between 220 and 500 mg/l (Davie, 2003).

COD, the chemical oxygen demand (mg/l) is a measure of the amount of organic matter that can be oxidised with a known strong oxidation agent under extreme conditions. The amount consumed oxidation agent is translated to mg Oxygen/l. The COD value is usually 2-3 times higher than the BOD value in settled, untreated wastewater (VAV, 1996).

Nitrogen exists in many forms: organic N (e.g. proteins and urea), ammonia, NH_3 or NH_4^+, nitrite, NO_2^-, and nitrate, $\mathbf{NO_3^-}$. Nitrogen levels in raw sewage vary depending on the diet of the local people. It ranges from 20 to more than 100 mg/l (Pescod, 1992). Nitrogen exists as organic N; mainly as ammonium ion, NH_4^+. In the presence of nitrifying bacteria and oxygen, NH_4^+ and organic nitrogen are oxidised to NO_2^- and NO_3^- (nitrification). NO_3^- is the crop available form of nitrogen and is added as fertiliser to enhance crop production. However NO_3^- in abundance may cause excessive vegetative growth, lodging and delayed crop maturity (Pescod, 1992).

Phosphorus (P) is present in three forms; organic phosphorus, polyphosphate and orthophosphate (usually just called phosphate), $\mathbf{PO_4^{3-}}$. Sewage can contain 5 to 50 mg/l P depending on the local diet (Pescod, 1992). Other sources are detergents and fertilisers. Phosphorus is a limiting factor for plants and the plant available form is PO_4^{3-}.

Chloride, $\mathbf{Cl^-}$, is most occurring in the common salt form (NaCl). It can be found in brackish water contaminated by seawater or in groundwater aquifers with high salt content. Chloride may also indicate sewage pollution, as the chloride content in urine is high (Pescod, 1992, Davie 2003). Chloride can accumulate in plant leaves and is toxic to plants. The most sensitive crops are affected by concentrations of 3.3 $mmol_c$/l (117 mg/l) (Pescod, 1992).

High sodium ($\mathbf{Na^+}$) concentrations, in relation to calcium ($\mathbf{Ca^{2+}}$) and magnesium ($\mathbf{Mg^{2+}}$), in soil water causes soil mineral to disperse and water penetration to decrease. To evaluate the sodium hazard of irrigation water, Sodium Adsorption Ratio, **SAR**, is often used. SAR measures the degree to which sodium in irrigation water replaces the adsorbed calcium and magnesium in the soil clays, and thus damages the soil structure (Hounslow, 1995).

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}}$$

where concentrations are expressed in mol_c/l.

Sodium can also be toxic to plants as an accumulation in plant leaves occurs and causes damage.

Potassium ($\mathbf{K^+}$) is an essential nutrient for plant growth and is the seventh most common element in the earth's crust. Although potassium is a relatively abundant element, its concentration in natural fresh waters is usually less than 20 mg/l. Sulphate ($\mathbf{SO_4^{2-}}$) is an abundant ion and its concentration can range from mg/l to several thousands. Sulphate is a product of the breaking down of sulphur-containing organic matter (WHO, 1996).

3.5 EVALUATION OF WATER QUALITY

Wastewater is not to be considered as a heterogeneous group of waters with the same quality, but should be looked upon as rather diverse. The composition of wastewater varies a lot depending on its origin, i.e. domestic or industrial. The constituents may also be more or less diluted. Some major constituents of typical domestic wastewater have been identified, and depending on the concentrations of the components the wastewater may be classified as strong, medium and weak (Table 1) (UN DTCD, 1985).

Table 1 Classification of strength of wastewater

Constituent	Concentration mg/l		
	Strong	Medium	Weak
Total Solids	1200	700	350
TDS[1]	850	500	250
Suspended Solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chloride[1]	100	50	30
Alkalinity (as $CaCO_3$)	200	100	50
Grease	150	100	50
BOD_5[2]	300	200	100

[1] The amounts of TDS and Chloride should be increased by the concentrations of these constituents in the carriage water.

[2] BOD_5 is the biochemical oxygen demand at 20 ºC over 5 days and is a measure of the biodegradable organic matter in wastewater.

Source: UN Department of Technical Cooperation for Development (1985)

The wastewaters also contain dissolved salts and nutrients that may be of good, or bad, from an agriculture point of view. Four problem categories related to irrigation water quality are identified. These are salinity, water infiltration rate, toxicity and other, miscellaneous problems (Ayers *et al.*, 1985) (Table 2) The osmotic pressure increases in soil water with high salinity, and plants have to use more energy to take up water (Pescod, 1992). This results in an increase in respiration and a decrease of plant growth and yield. The water infiltration rate is influenced by the salinity and the Sodium content relative Calcium and Magnesium content (i.e. SAR). Water of high salinity will increase infiltration and water with low salinity or a high SAR-value will decrease infiltration. The constituents responsible for toxic effects are mainly Sodium, Chloride and Boron. Accumulation in plant leaves can cause damage to crops or reduced yield. Several trace elements also influence plant growth; some are essential (in reasonable amounts) for plant growth (Fe, Mn, Mo and Zn) while others are toxic already at small concentrations. Recommended maximum irrigation water levels for crop production have been developed (NAS, 1972 Pratt, 1972). Miscellaneous problems are e.g. excessive vegetative growth, lodging and delayed crop maturity due to high nitrogen concentrations, and deposits on fruit and leaves by sprinkler irrigation with high bicarbonate water. Water with pH outside the normal range (6.5-8) is an indication of abnormal water (Ayers *et al.*, 1985).

Table 2 Guidelines for interpretation of water quality. Adapted from University of California Committee of Consultants 1974

Potential irrigation problem	Units	Degree of restriction on use		
		None	Slight to moderate	Severe
Salinity				
EC_w[1]	dS/m	< 0.7	0.7 – 3.0	>3.0
or				
TDS	mg/l	< 450	450 - 2000	> 2000
Infiltration				
SAR[2] = 0-3 and EC_w		> 0.7	0.7 – 0.2	< 0.2
3-6		> 1.2	1.2 – 0.3	< 0.3
6-12		> 1.9	1.9 – 0.5	< 0.5
12-20		> 2.9	2.9 – 1.3	< 1.3
20-40		> 5.0	5.0 – 2.9	< 2.9
Specific ion toxicity				
Sodium (Na)				
Surface irrigation	SAR	< 3	3 – 9	> 9
Sprinkler irrigation	$mmol_c/l$	< 3	> 3	
Chloride (Cl)				
Surface irrigation	$mmol_c/l$	< 4	4 – 10	> 10
Sprinkler irrigation	$mmol_c/l$	< 3	> 3	
Boron (B)	mg/l	< 0.7	0.7 – 3.0	> 3.0
Miscellaneous effects				
Nitrogen (NO_3-N)[3]	mg/l	< 5	5 – 30	> 30
Bicarbonate (HCO_3)	$mmol_c/l$	< 1.5	1.5 – 8.5	> 8.5
pH		Normal range 6.5 – 8		

[1] EC_w means electrical conductivity in deciSiemens per metre at 25 ºC

[2] SAR means sodium adsorption ratio

[3] NO_3-N means Nitrate Nitrogen reported in terms of elemental Nitrogen

Source: Ayers R.S., Westcot C.W., 1985. Water Quality for Agriculture - FAO irrigation and drainage paper 29.

Ayers *et al.* (1985) classify the quality of irrigation water in reference to the degree of restriction on use. The three classes are ‘none’, ‘slight to moderate’ and ‘severe’ (Table 2). When irrigating with water that falls under the ‘no restriction on use’ category, no soil or cropping problems are experienced. Using water in the slight to moderate range may cause problems. It requires less sensitive crops and a more advanced management scheme. If water falls in the category for severe restriction, the farmer will experience soil and cropping problems. An even higher level of management skills is essential for acceptable production.

The Pollution Control Board (PCB) in India has specified parameters to classify water sources based on designated best use. For water considered suitable for irrigation EC, SAR and Boron should not exceed 2.25 dS/m, 26 and 2 mg/l, respectively. pH should fall between 6.5 and 8.5 (PCB, 2003).

3.6 WASTEWATER TREATMENT

Most treatment techniques have been developed in temperate northern climates and are often not suitable for developing countries as the energy requirement is high as are the operation and maintenance costs (including production of large quantities of sludge) (Parr, 2005). Most conventional treatment processes are aerobic and oxygen is supplied mechanically, resulting in high costs and a demand for skilled labour. The conventional treatments are not designed for human health protection; the main focus is to protect the environment (removal of nutrients). The reduction of faecal coliforms is not sufficient (Parr, 2005). The anaerobic (oxygen absent) processes are simpler and cheaper to run and benefit from high temperatures, thus suitable in developing countries in hot regions. But to remove pathogenic organisms (above all, bacteria) the anaerobic process needs to be complemented with a pathogen-removing step.

The choice of treatment technique is governed centrally and decisions are based on current fashions and, often, prestige. Many of these systems are expensive to build, and have high operational and maintenance costs. Hence, many treatment plants do not operate properly and as a result pollution and health problems are severe (Parr *et al.*, 1999). The access to drinking water is often a bigger and more acute problem and therefore the municipal councils tends to prioritise water supply schemes before sewage treatment, or maintenance of existing treatment works.

Primary treatments are common in most treatment plants. Coarse material and settable solids are removed by screening, grit removal and sedimentation. There exist many options for secondary treatment, some more suitable than others. Blumenthal *et al* (2000) mention the following as good alternatives in low-income countries: Soil Aquifer Treatment (SAT), constructed wetlands, Upflow Anaerobic Sludge Blanket (UASB) and Waste Stabilisation Ponds (WSP). They all have in common that no oxygen is mechanically supplied.

In Soil Aquifer Treatment, sewage is supplied to the soil, under controlled conditions. In constructed wetlands the sewage flows through an area of reeds. UASB is an anaerobic process and in a WSP, the sewage runs through a series of ponds and the treatment is by action of sunlight, sedimentation and encouragement of algal growth, which provides the pond with oxygen (UASB and WSP are described in more detail below).

In low-income countries, where the reuse of wastewater in agriculture is common, the main issue is pathogen removal. The most suitable treatment option is Wastewater Stabilisation Ponds (Shuval *et al.,* 1986). A comparative study in Colombia shows that even if the performance of an anaerobic pond (in a WSP system) and an UASB is almost equal, there are economical advantages with the anaerobic pond. The construction and maintenance cost are 16% and 38 %, respectively, lower for an anaerobic pond compared to an UASB (Peña *et al*., 2000).

3.6.1 Uplow Anaerobic Sludge Blanket

The principle behind the upflow anaerobic sludge blanket, UASB, is anaerobic digestion and aggregation of sludge particles (Figure 7). The inflow passes through the anaerobic sludge bed and the bacteria in the sludge come in contact with the incoming wastewater. The sludge bed consists of microorganisms that naturally forms granules with high sedimentation velocity and thus are resistant to wash out. The anaerobic digestion produces gas which gives rise to a spontaneous mixing of the tank. A three-phase separator on the top of the reactor separates gas, solids and liquid. In temperate climates the UASB reactor is used mainly for industrial effluents but in warm climates, as in India, it functions very well for domestic sewage. The COD removal is 85-95% (Field, 2002).

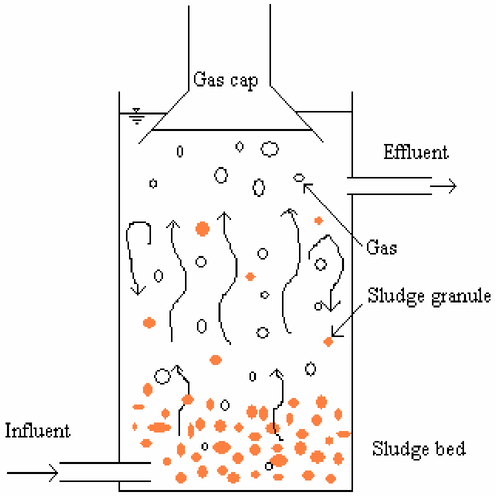

Figure 7 Schematic drawing of an USAB tank. Source: www.uasb.org

To meet the microbiological quality guidelines for wastewater reuse, the UASB effluent needs to undergo further treatment, e.g., through a wastewater stabilisation pond system (Dixo *et al.,* 1995).

3.6.2 Wastewater Stabilisation Ponds

Wastewater Stabilisation Ponds (WSP) consists of a single series of anaerobic, facultative and maturation ponds or several series in parallel (Figure 8). Depending on the strength of the incoming wastewater and requirements on the final effluent, the WSP can be designed in many different manners (Pescod, 1992).

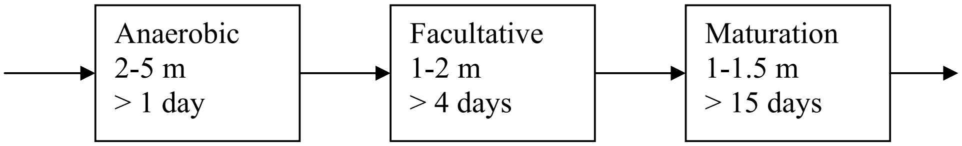

Figure 8 Schematic drawing of wastewater stabilisation ponds in series with average pond depths and minimum retention times. The pond sizes are not to scale.

Anaerobic ponds are normally 2-5 meters deep and function as open septic tanks (Pescod, 1992). The retention time should not be less than one day (McGarry *et al.*, 1970). To maintain anaerobic conditions, the volumetric BOD loading should not be below 100 g/m^{3}day and, to avoid odour, not exceed 400 g/m^{3}day (Meiring *et al.*, 1968).

The primary function of the anaerobic pond is BOD removal (Mara 1997, Pescod 1992). This is mainly achieved by sedimentation of solids and anaerobic digestion of organic material in the resulting sludge layer. The organic material is released as carbon dioxide and methane gas. Helminth eggs and solid associated bacteria are removed by sedimentation. There is no nitrification or denitrification but organic nitrogen is hydrolysed to ammonia (Mara, 1997).

Anaerobic ponds work very well in high temperatures. The BOD removal can reach, for example, 60% at 20 ºC and 70% at 25 ºC (Mara 1997).

Facultative ponds normally have depths between 1-2 meters. They function at rather low surface BOD loadings, approximately 100-400 kg/ha,day, in order maintain aerobic conditions (Mara, 1997). A minimum retention time of 4 days should be adopted to prevent algal washout.

The main purpose is BOD removal, and a facultative pond can either be primary or secondary. Primary facultative ponds receive raw sewage water and secondary receives settled sewage water (anaerobic pond effluent). In the secondary facultative ponds, the non-settleable BOD is oxidised by heterotrophic bacteria. The oxygen is generated by photosynthesising algae that, in turn, depend on the carbon dioxide provided by the bacteria. It thus exists a mutualistic relationship between the two. Instead of escaping to the atmosphere the carbon dioxide is used by the algae to increase its biomass. One might say that sewage BOD transforms into algal BOD (Mara, 1997).

Ammonia is incorporated into algae and will eventually settle and be immobilised. Unless the concentration of NO_3^- is high, no denitrification will take place. The removal of phosphorus is due to settling of organic P, incorporation to algae biomass, and precipitation of inorganic P.

The functions of the anaerobic and the facultative pond are combined in primary facultative ponds.

The facultative ponds are usually green in colour due to the algae. One important factor is the wind as a thorough mixing of oxygen, bacteria, algae and organic material enhance the BOD removal.

The **maturation ponds** (1-1.5 m deep) are usually more than one in a series. They receive the facultative pond effluent. The primary function of maturation ponds is pathogen removal and the quality requirements of the effluent determine the number of ponds necessary. The BOD removal is low (Mara, 1997).

The bacterial die off is dependent on time, temperature pH, light intensity and dissolved oxygen (Feachem *et al*., 1983). pH values of 9 and above are common in ponds due to the rapid consumption of CO_2. The bacterial die off is very rapid at pH > 9 (Pearson *et al*., 1987).

As in facultative ponds, ammonia is incorporated into new algal biomass. Furthermore, removal of phosphorus follows the same pattern as in facultative ponds.

Removal curves for BOD, helminths, bacteria and viruses in a WSP system are shown together in Figure 9. Most of the nematodes are removed during the anaerobic phase, bacteria and viruses during the facultative and maturation phases. BOD is removed throughout the anaerobic and facultative phases.

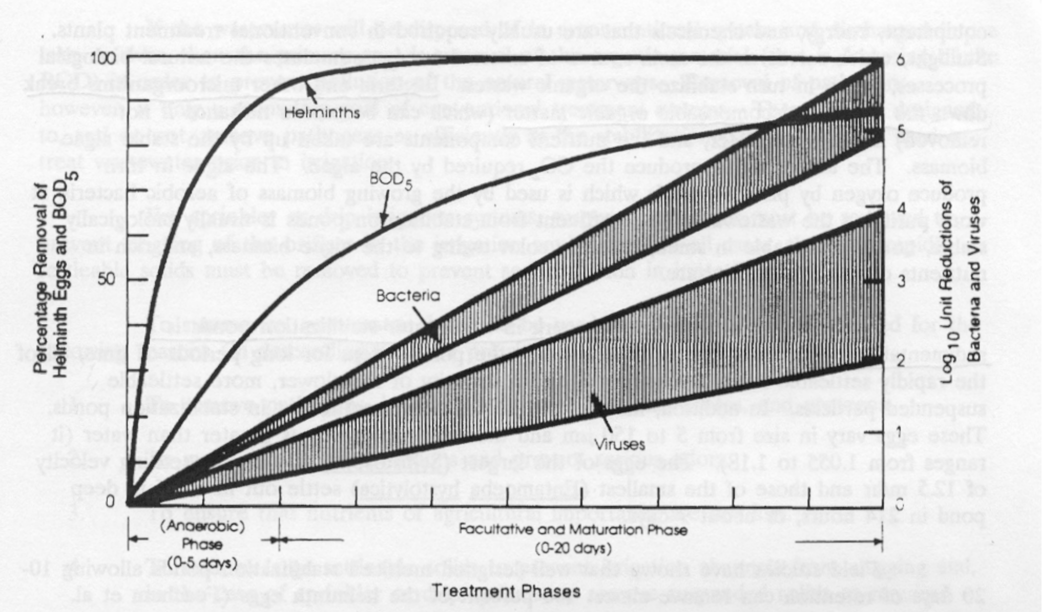

Figure 9 Generalised removal curves for BOD, helminth eggs, bacteria and viruses in waste stabilisation ponds at temperatures above 20°C. Source: Shuval H.I. *et al.*, 1986. Wastewater irrigation in developing countries, health effects and technical solutions. World Bank Technical Paper 51.

In a WSP, an overall retention time of 20 days will produce an effluent free of intestinal nematode eggs and protozoan cysts (Feachem *et al.*, 1983).

4 METHODS

4.1 STUDY SITE DESCRIPTION

Hyderabad with its 6 million inhabitants (2001) is the capital and the largest city in the state Andhra Pradesh, India. The city is growing fast and had a 29% increase in population from 1990 to 2000 (UN, 2001). It is situated at Lat 17.45 N, Long 78.46 E at 545 meters above sea level.

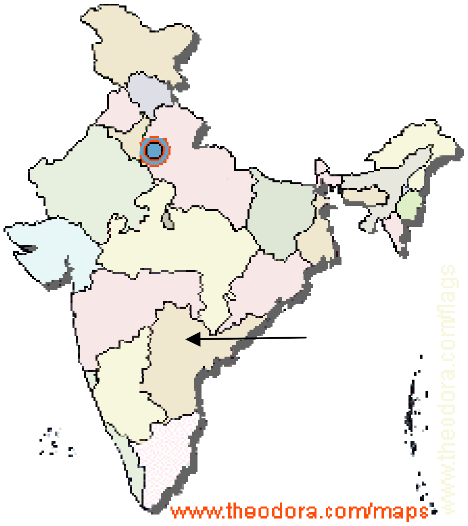

Figure 10 Map of India. Andhra Pradesh and Hyderabad are pointed out. Maps courtesy of www.theodora.com/maps, used with permission.

The city with its nine surrounding municipalities encompasses an area of more than 500 km^2. The average temperature varies from 20˚C in December to 32˚C in May and the average annual rainfall is 890 mm, 680 mm of those fall during the south-west monsoon seasons, i.e., from June to September (Icrisat, 2004). The rapid growth of the city has led to an increase in water use and, consequently, an increase in the amount of domestic sewage produced. The city's sewage system was built in 1931 for an estimated population of 470 000 over an area of about 87 km^2. According to the Hyderabad Metropolitan Water Supply and Sewage Board (HMWSSB, 2005) the treatment plant of that time had the capacity of 44 000 m^3/day. The existing plant (2004) was built in 1992 and has a capacity of 115 000 m^3/day. An additional treatment plant, adjacent to the Lake Hussein Sagar, treats 20 000 m^3/day. The total volume treated is thus 135 000 m^3/day. The treatment in the existing plant is primary, but the detention time in the tanks is short (2-2½ h) and the BOD removal efficiency is only 30%. The BOD outflow is approx 250 mg/liter (Reddy, 2004).

The Musi River runs through the city from east to west and interceptor sewers follow both banks of the river (Figure 11). The two sewers connect at one point and run 3 km towards the east to the existing plant.

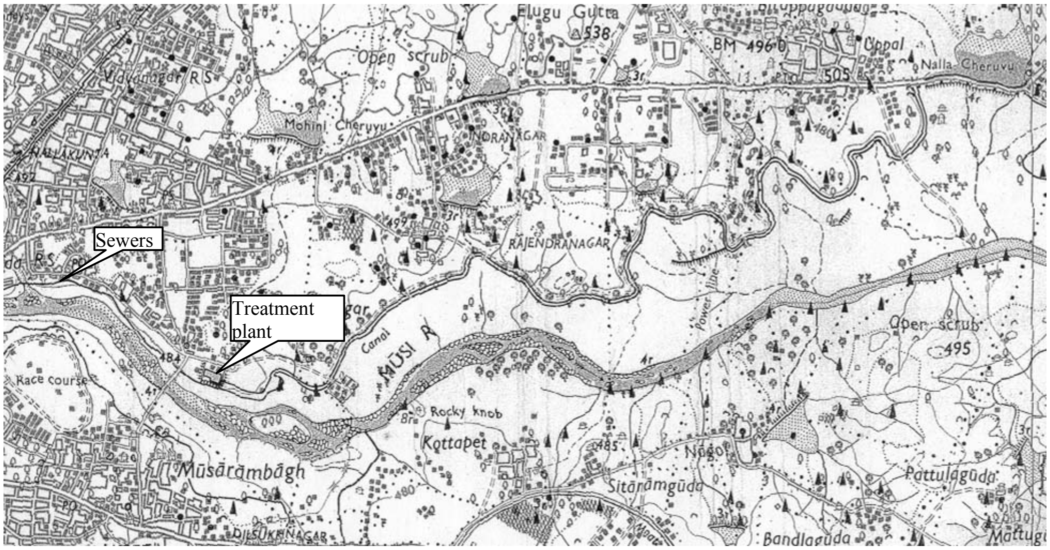

Figure 11 Map of Musi River leaving Hyderabad. The sewers, the treatment plant and the two canals leading the treatment plant effluents to the Nalla Chevuru tank are shown.

The increase in population has resulted in severe overloading of the sewerage and causes overflows into open surface drains. New sewer lines have been built but are not all connected to the interceptors that lead to the treatment plant. The main lines were laid inside the storm water drains, which carry rainwater to different water bodies around the city and into the Musi River. These water bodies, or tanks, built to store rainwater, are thus highly polluted with domestic sewage. The total inflow to the treatment plant is 250 000 m^3/day but only 115 000 m^3/day is treated, the remaining 135 000 m^3 is diverted around the treatment plant and both the treated and untreated effluent is disposed in one such tank, Nalla Chevuru. This is shown on the map in figure 11 where the tank is in the upper right corner. It is estimated that a total of 900 000 m^3 is let to the city drains every day. Only 15% of the sewage generated in the city is treated in any way.

The Hyderabad Metropolitan Water Supply & Sewage Board is planning a Musi River Conservation Project with five new sewage treatment plants, increasing the treatment capacity to 592 000 m^3/day (HMWSSB, 2005). The planned new plants are all Upflow Anaerobic Sludge Blanket -plants (UASB) (Reddy, 2004).

The Musi River originates in the Anantha Giri Hills 90 km west of Hyderabad. Upstream of Hyderabad a reservoir was constructed in the 1922, designed to be a flood moderator and to supply Hyderabad with drinking water. There is no water in the river as it enters the city, except during the monsoon season. Downstream, nevertheless, the river is perennial, due to the vast amounts of wastewater disposed.

It is estimated that 250 households within the city use wastewater directly from the drains or from the river, to irrigate approximately 600 ha of land (Beuchler *et al.*, 2002). The main crops cultivated in this urban area are paragrass (fodder), banana, coconut and green leafy vegetables.

Downstream of Hyderabad the water is diverted, with the help of weirs, into irrigation canals. The first weir, 9.6 km downstream of Hyderabad, and the two irrigation canals are shown in Figure 12.

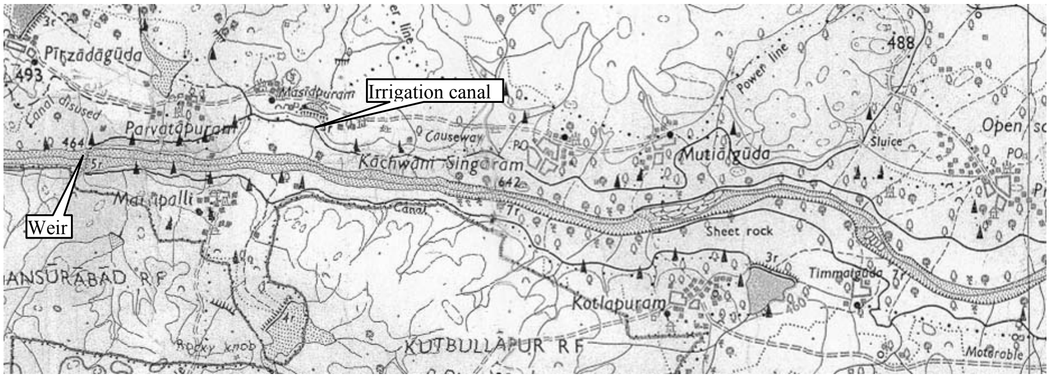

Figure 12 Map showing the first weir downstream of Hyderabad. The irrigation canals diverted is also seen.

The area depending on Musi for irrigation water all the way till it joins the Krishna River is estimated to 40 000 ha and Musi water irrigated area within the study area is estimated to lie between 3500 and 4000 ha (Ensink, 2005). The main crops grown in this peri-urban area are paragrass (fodder), rice and green leafy vegetables as spinach and fenugreek. Flood irrigation is practised.

4.2 SAMPLE POINT SELECTION

4.2.1 River

The aim was to find points that differed in intestinal nematode concentrations. Water quality at the different sampling points would, ideally range from untreated wastewater to current and proposed WHO guideline values. The selection of sample points was further 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 (Ensink, 2003).

4.2.2 Reservoir

The first weir is located 9.6 km downstream of Hyderabad, where the flow slows down resulting in the sedimentation of suspended particles, including helminth eggs.

Water and sediment samples was analysed concerning nematodes at four different locations along the weir and at one location upstream. The locations were chosen where water was still and sedimentation would occur. The accessibility to still water without having to enter the reservoir determined the exact sampling locations.

4.2.3 Irrigation canal

From the first weir, 9.6 km downstream of Hyderabad, two canals are diverted. Along the north canal four sampling points was selected within equal distance. The canal is about 5 metres wide and 1 metre deep. According to an inscription at the site, the discharge to the north canal is 342 521 m^3/day but the flow measured close to the inlet in March and February 2004 was 284 000 m^3/day (Hytteborn, 2005). The water is let into the fields either by pumping or by small openings in the canal wall. The farmers control the inlet by removing an obstacle (rocks or soil). Some locations have wells dug next to the canal, where the water infiltrates and from where the pumping to the fields takes place. The water in two of those wells was analysed for nematodes.

4.3 DATA COLLECTION

River samples for intestinal nematode eggs, DO and EC analyses, was collected on a biweekly basis and BOD and *E.coli* on a monthly basis. The above data collection was part of an ongoing research project (Ensink, 2003), where also samples for trace element analyses were collected at different locations on two to four occasions. The irrigation canal was sampled on two occasions, for intestinal nematode eggs, BOD, DO and EC. The water in the reservoir was analysed for intestinal nematode eggs on three occasions and a sediment sample analysis was done once. The above data is referred to as IWMI data.

Water quality data was also gathered from the Andhra Pradesh Pollution Control Board, which monitors the Musi River. Samples are taken from many locations but only the ones coinciding with the chosen sampling points for the IWMI project were included in this work. The data obtained from the Pollution Control Board is referred to as PCB data.

4.4 FLOW MEASUREMENTS

Flow was measured using the Velocity-Area method and the Float method was used to determine the velocity (James, 1988).

$$Q = VA \qquad \mathrm{m^3/h} \qquad \textbf{Equation 1}$$

Where Q = flow, m^3/h,
A = area of river cross section, m^2
V = average velocity of the stream m/h

The average velocity was obtained by timing a float travelling a known distance. The velocity of the float was then multiplied with a velocity correction factor dependent on the average depth of the river at the cross section (Table 3).

Table 3 Correction factor for surface velocity to average velocity of stream

Average flow depth (m)	Correction factor	Average flow depth (m)	Correction factor
0.3	0.66	1.8	0.76
0.6	0.68	2.7	0.77
0.9	0.70	3.7	0.78
1.2	0.72	4.6	0.79
1.5	0.74	≥6.1	0.80

Source: U.S. Bureau of Reclamation, *Water Measurement Manual* (1975), Department of the Interior, U.S. Government Printing Office, Washington, D.C., 327 pp.

The flow was measured at the first sampling point every time water quality samples were collected.

4.5 ANALYSIS

4.5.1 Nematodes in water

The enumeration of helminth eggs was done according to the Bailinger method (Ayers *et al.*, 1996). In short: 5 litres samples were collected in plastic cans and left over night to settle. The supernatant (approximately 90 %) was removed and the sediment transferred to a one-litre beaker. The sample was left to settle for 2 hours before the supernatant was removed and the sediment carefully transferred to centrifuge tubes. The tubes were centrifuged at 1000 g for 15 min. The supernatant was removed and the pellet suspended in an equal volume acetoacetic buffer. Two volumes of ethyl acetate were added and the suspension mixed thoroughly. The samples were centrifuged again at 1000 g for 15 min. The pellet was suspended with zinc sulphate solution, to a known volume, until the sample was clear enough for identification under the microscope. (Some adjustments of the original method were made as follows; 5 litres were collected instead of 10 and zinc sulphate solution was added until the sample was clear enough as opposed to five volumes.)

4.5.2 Nematodes in sediment

Sediment was sampled with a scoop and kept in airtight jars. Approximately 5 g (5 ml) of sediment was transferred to centrifuge tubes. Acetoacetic buffer was added up to 15 ml and thereafter ethyl acetate was added to 30 ml. The suspension was mixed thoroughly and centrifuged at 1000 g for 15 min. The pellet was suspended with zinc sulphate solution to a known volume, until the sample was clear enough for identification under the microscope. To express the number of eggs per dry weight sediment, corresponding sediment samples were weighed and dried to determine water content.

4.5.3 E coli

Testing for *Escherichia coli* was done using the membrane filtration technique. Samples were collected in sterile 500 ml glass bottles. The bottles were stored in a cool box and processed within 6 hours of sampling. The samples were diluted accordingly and filtered through a membrane with pore size 0.45 µm. The membrane was put on a sterile petri dish containing an absorbent pad soaked with m-ColiBlue24® broth (Hach Company, product #2608450). The samples were incubated in 37 ˚C for 24 hours. *E coli* produce blue colonies (Figure 13) that were counted and the concentration calculated.

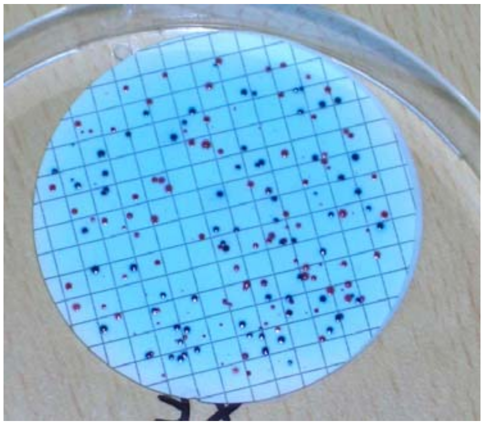

Figure 13 Membrane containing *E coli* colonies (blue).

4.5.4 Other water quality parameters

BOD_5 was be analysed by EPTRI[4]. Standard methods as specified by the American Environmental Association were used. One-litre samples were collected in airtight bottles, and the samples were processed within 6 hours of sampling. EC and DO were measured in situ using a handhold meter (Model YSI 85, Ohio, USA). The identification of other interesting water parameters, such as heavy metals, nutrients and different ions was made at the local laboratory at the ICRISAT Campus.

4.6 RETENTION TIME OF RESERVOIR AND REMOVAL EFFICIENCIES

The **hydraulic retention time** is based on the volume of the reservoir and the mean flow (Equation 2).

$$\theta_h = \frac{V}{Q}$$ **Equation 2**

Where θ_h = hydraulic retention time, day
V = reservoir volume, m^3
Q = flow, m^3/day

Assuming the inflow equals the outflow, i.e. the volume is constant, the flow used is the sum of the discharge flow, measured at the first sampling point, and the direct precipitation on the reservoir surface. Daily rainfall is calculated from a total yearly divided by 365. Daily discharge from the city is based on monthly averages of daily flow.

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[4] The Environmental Protection Training and Research Institute in Hyderabad

The volume of the reservoir is estimated by assuming that the cross section resembles half an ellipse and that the area of the reservoir has simple geometric form as described in Figure 14.

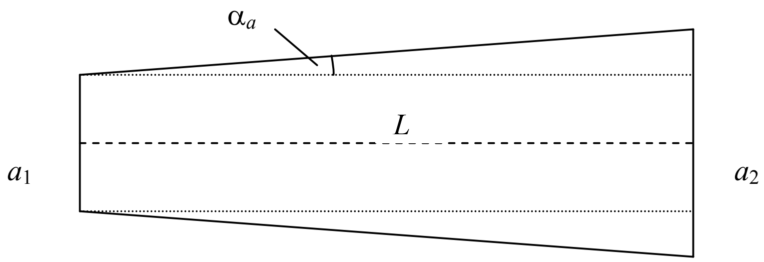

Figure 14 Schematic drawing of the reservoir (as seen from above). L is the length of the reservoir, a_1 is half the width at the narrow end, and a_2 is half the width at the wide end. α_a is the angle that describes the widening of the reservoir.

The area of half an ellipse is:

$$A = \frac{\pi}{2} ab$$ **Equation 3**

Where A = area of the cross section, m^2
a = long radius, m
b = short radius, m

To find the volume, the area of the cross section is intergraded over the length of the reservoir.

$$V = \int A dL$$ **Equation 4**

Where L=length of reservoir, m
A=area of cross section, m^2

One can express the radiuses at the wide end of the reservoir as functions of the radiuses at the narrow end and the length of the reservoir (figure 14) as follows:

$$a_2 = a_1 + L \tan \alpha_a$$ **Equation 5**

$$b_2 = b_1 + L \tan \alpha_b$$ **Equation 6**

Where L = length of reservoir, m
α = the angle (Figure 14)
a_1, a_2, b_1, b_2 = long and short radiuses at the narrow and the wide end (Figure 14)

Combining equation 3; 4, 5 and 6 gives the final equation for calculation of the reservoir volume:

$$V = \int \frac{\pi}{2}(a_1 + L\tan\alpha_a)(b_1 + L\tan\alpha_b)dL$$ **Equation 7**

With knowledge of volume and in-flow the hydraulic retention time can be estimated using Equation 2. The estimated retention time is then used as an in-parameter in design equations for BOD-, *E coli*- and nematode removal to compare the efficiency of the reservoir with a designed WSP system.

A design equation for egg removal has been developed (through studies in Kenya and Brazil) for designing wastewater stabilisation ponds (Ayers *et al.,* 1992a):

$$R = 100[1 - 0.41\exp(-0.38\theta)]$$ **Equation 8**

Where R = percentage egg removal
θ = retention time in days

Equation 8 is equally valid for anaerobic, facultative and maturation ponds.

Assuming **faecal coliform removal** can be modelled by first order kinetics, Marias (1974) developed the following equation, valid for a completely mixed, single pond:

$$N_e = \frac{N_i}{(1 + k_T\theta)}$$ **Equation 9**

Where N_e = number of faecal coliforms per 100 ml in the final effluent
N_i = number of faecal coliforms per 100 ml in influent (raw wastewater)
k_T = first order rate constant for faecal coliform removal, day^{-1}
θ = retention time, days

The value of k_T is highly temperature dependent. Marias (1974) found that:

$$k_T = 2.6(1.19)^{T-20}$$ **Equation 10**

Where T = temperature, °C

The temperature used is the mean ambient temperature based on yearly data (ICRISAT, 2004).

The completely mixed flow model (Equation 9) (Marias, 1974) with the assumption of first-order kinetics for **BOD removal** can be used for designing facultative ponds (Pescod, 1992). By substituting N_e and N_i with concentrations of BOD in effluent and influent the following relationship for BOD removal is found:

$$C_e = \frac{C_i}{(1 + k_T\theta)}$$ **Equation 11**

Where θ = retention, days
C_e = BOD in effluent, mg/l

C_i = BOD in influent, mg/l
k_T = first order rate constant for BOD removal, day^{-1}

The rate constant for BOD removal is dependent on temperature in the following manner (Mara, 1994):

$$k_T = 0.3(1.05)^{T-20}$$ **Equation 12**

Where T = temperature, °C

The temperature used is the mean ambient temperature based on yearly data (ICRISAT).

4.7 STATISTICAL ANALYSIS

Instead of conducting ordinary Student t-tests to test for differences between all sampling points, a multiple comparison method was chosen. To compare *k* means with an ordinary Student t-test would require *k(k-1)/2* tests and the α-value would be appropriate for each individual comparison, but not for the set of all comparisons (Weisstein, 2005). The Bonferroni multiple comparison method was used (Johnson, 2000). This method corrects the α-value by dividing α with the number of comparisons (*k(k-1)/2*) to avoid Type I[5] errors. The individual test critical values are then $\leq \alpha/(k(k-1)/2)$ and the experiment-wide critical value is $\leq \alpha$ (Weisstein, 2005).

The data was first tested for normality and outliers were identified and excluded. The statistical analyses on faecal coliforms were performed on $\log_{10}$ values (equivalent to geometric mean) to obtain normality and linearity. The statistical software used was MINITAB 14.

4.8 MAPS

Maps showing the study area, sampling sites and reservoir area were made using the GIS software ArcGIS 9. Coordinates were identified using a hand held Global Positioning System receiver. The satellite images used were kindly provided by International Water Management Institute in Hyderabad.

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[5] A Type I error is when the null hypothesis is true but rejected i.e., one say that there exists a difference but in fact there is none.

5 RESULTS

5.1 WATER QUALITY ALONG THE RIVER

The data presented from IWMI was collected from June 2003 to May 2004. The sampling points (I to VII) and the locations of the weirs are presented in figure 13 and table 4.

Table 4 Name and location of the sampling points

Sampling point	Area /Village	Distance (km) from the centre of Hyderabad
I	Amberpet (Hyderabad)	0
II	Nagole (Hyderabad)	5.3
III	Peerzadiguda	9.6
IV	Mutialguda/ Kotlampuram	13.9
V	Gourvelli	17.5
VI	Koremalla	20.2
VII	Pillaipally	28.7

Between the first sampling point and the last, the distance is 28.7 km, and the number of reservoirs formed by weirs is eight. At the sampling points adjacent to weirs the sample was taken downstream of the reservoir.

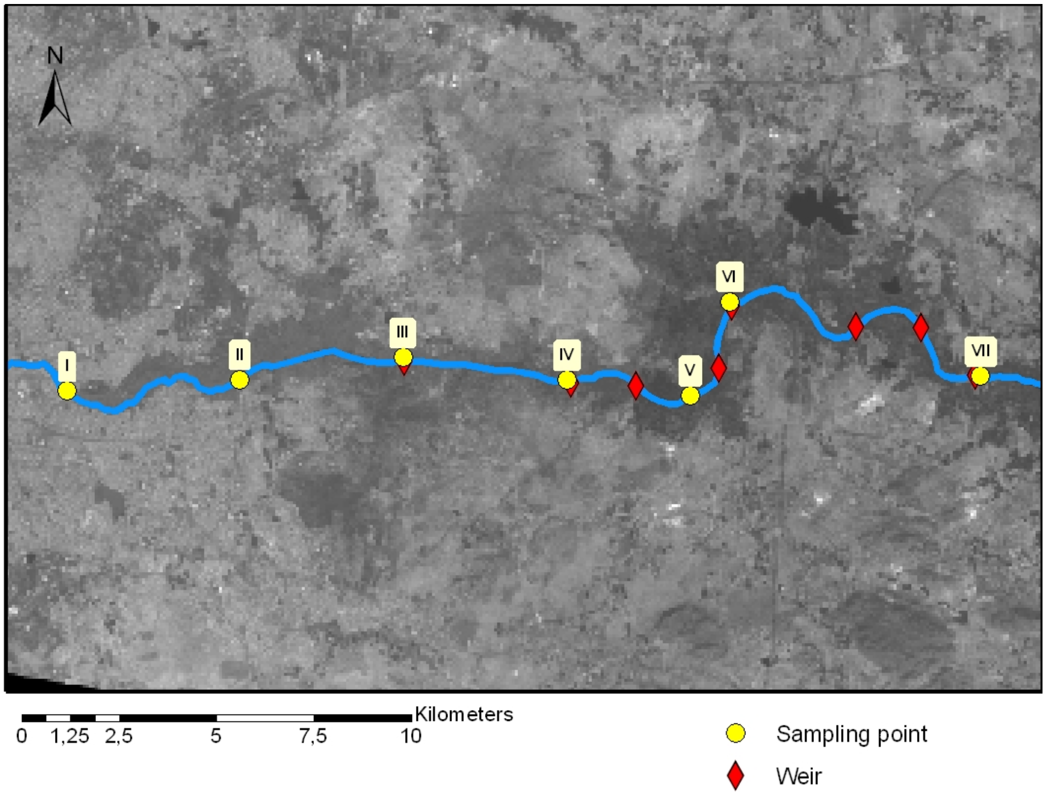

Figure 15 The sampling points (I-VII) and the locations of the weirs on Musi River, downstream of Hyderabad

At the first and second sampling points the water is very turbid, containing a lot of suspended material. At the third point, the water is a little bit clearer as some of the settleable solids have been removed in the first reservoir. After the second reservoir, at sampling point IV, the water is even clearer. Between IV and VI it is difficult to determine with the naked eye if the water gets clearer but at VII additional solids have settled (Figure 16).

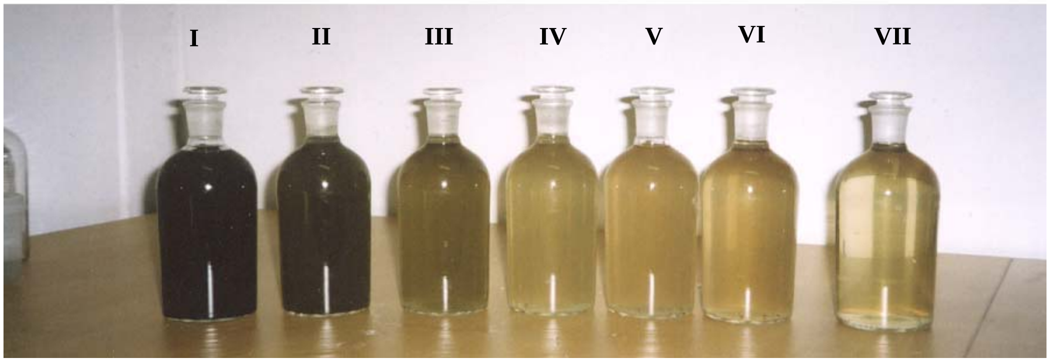

Figure 16 Water samples collected at the different sampling points along the Musi River.

The results of the IWMI data collection are presented in Table 5. The results from the IWMI measurements show a decrease in BOD_5, from 237 mg/l, to 31 mg/l at sampling point VII. This corresponds to a total BOD-removal of 89%. Between II and III the removal is 56 %. The dissolved oxygen, DO, is very low up to point VII. The EC increases downstream, from 1.63 dS/m at the first sampling point to 2.16 dS/m at the last. Total dissolved solids seem to follow the same pattern but the sample size is too small to verify this statistically. pH tends to be higher downstream.

Table 5 Water quality parameters expressed as average values with standard deviation in parenthesis. Data from IWMI, Hyderabad, June 2003 to May 2004

Sampling point	pH[*]	BOD$_5$ mg/l	DO mg/l	EC dS/m	TDS[*] mg/l
I	7.1	237^{a}	0.12^{a}	1.63	1009
	(0.04)	(96)	(0.11)	(0.18)	(5)
	n=2	n=5	n=11	n=13	n=2
II	7.5	285^{a}	0.13^{a}	1.92^{a}	1062
	(0.21)	(84)	(0.09)	(0.16)	(127)
	n=2	n=5	n=13	n=13	n=2
III	7.6	125^{b}	0.12^{a}	2.15^{ab}	1136
	(0.13)	(46)	(0.10)	(0.25)	(97)
	n=4	n=7	n=13	n=15	n=4
IV	7.9	69^{bc}	0.12^{a}	2.14^{ab}	1086
	(--)	(28)	(0.11)	(0.17)	(--)
	n=1	n=4	n=12	n=12	n=1
V	8.0	61^{bc}	0.20^{a}	2.10^{ab}	1082
	(0.02)	(15)	(0.23)	(0.16)	(76)
	n=2	n=5	n=13	n=13	n=2
VI	7.9	53^{bc}	0.89^{a}	2.17^{b}	1208
	(0.03)	(20)	(1.16)	(0.21)	(244)
	n=3	n=6	n=10	n=12	n=3
VII	8.0	31^{c}	2.71	2.16^{b}	1248
	(0.05)	(20)	(1.44)	(0.19)	(209)
	n=4	n=7	n=13	n=14	n=4

^{abc} Two adjacent means that share the same superscript are not significantly different (P=0.05) using the Bonferroni multiple comparison method.

n=sample size.

[*] Statistical analysis not performed. Sample size too small

The Pollution Control Board data was collected from July 1998 to June 2000 (with the exception of some measurements from December 1993 and February 1994). The upstream data is from January 1995 to July 2000. Table 6 shows the data obtained from the PCB. The water quality changes between the upstream location and the first sampling point in the city, sampling point I. All parameters, except Mg, are different at a 95 % level of significance.

The COD-value decreases downstream. The change is statistically significant at a 95% level. From I to VII the total COD-removal is 62 %. Over the first weir (between II and III) the removal is 26 %. The PCB results show an increase in EC and TDS, 1.32 dS/m to 1.74 dS/m and 822 mg/l to 1072 mg/l respectively, but the increase of EC and TDS between point II to VII is not statistical significant. The water pH increases slightly from 7.5 to 7.8. At VII, the pH is no different from the upstream location. The amounts of NO_3, PO_4, Mg and K are constant throughout the downstream river system. NO_3 varies from 8.2 mg/l to 9.9 mg/l, PO_4 from 1.2 mg/l to 1.4 mg/l, Mg from 38 mg/l to 48 mg/l and K varies from 27 mg/l to 30 mg/l. The same could be said for Na, where only the value at location III differs from location I. The lowest concentration of Na is at location I with 173 mg/l, and the highest at location III with 254 mg/l. The increase in concentrations of Cl and SO_4 are statistically significant between location I and II and between II and VII. At point I, Cl concentration is 177 and at VII 257 mg/l. The concentration of SO_4 at I is 88 and at VII 139 mg/l. The Ca increase is not statistically significant between location I and III but the concentration at location VII is different from I and II. The Ca concentration ranges from 88 to 139 mg/l. The calculated SAR value is constant from I to VII.

Table 6 Musi River water quality data obtained from Andhra Pradesh Pollution Control Board (PCB). The data is from 1998-2000 and expressed as average values with the standard deviation in parenthesis

Sampling point	pH	COD mg/l	DO mg/l	EC dS/m	TDS mg/l	NO_3 mg/l	PO_4^{3-} mg/l	Na^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	SAR	K^+ mg/l	Cl^- mg/l	SO_4^{2-} mg/l
Upstream	7.9^{a} (0.38) n=51	10 (4.5) n=51	7.2 (1.4) n=49	0.3 (0.06) n=51	237 (49) n=51	0.4 (0.3) n=35	0.01 (0.05) n=35	27 (12) n=44	48 (24) n=51	45^{a} (44) n=51	0.8 (0.3) n=44	NA	23 (12) n=51	9 (7) n=51
I	7.5^{b} (0.51) n=64	167 (61) n=64	NA	1.32 (0.33) n=64	822 (221) n=64	8.2^{a} (3.8) n=64	1.2^{a} (0.7) n=63	173^{a} (109) n=63	66^{a} (16) n=63	38^{a} (12) n=63	4.3^{a} (2.5) n=63	28^{a} (21) n=63	177 (63) n=64	88 (54) n=64
II	7.5^{b} (0.51) n=66	139 (52) n=66	NA	1.58^{a} (0.40) n=66	965^{a} (255) n=66	9.6^{a} (3.9) n=66	1.4^{a} (0.8) n=64	232^{ab} (159) n=66	71^{a} (15) n=66	41^{a} (14) n=66	5.3^{a} (3.4) n=66	27^{a} (11) n=66	222^{a} (60) n=66	113^{a} (48) n=66
III	7.6^{bc} (0.51) n=65	103 (35) n=64	NA	1.66^{a} (0.39) n=65	1026^{a} (261) n=65	9.9^{a} (4.8) n=65	1.4^{a} (0.8) n=64	254^{b} (159) n=65	76^{ab} (17) n=65	44^{a} (11) n=65	5.7^{a} (3.5) n=65	30^{a} (10) n=64	243^{ab} (58) n=65	129^{ab} (47) n=65
VII	7.8^{ac} (0.45) n=66	63 (39) n=65	6.3 (1.5) n=48	1.74^{a} (0.42) n=66	1072^{a} (268) n=66	8.5^{a} (4.5) n=66	1.2^{a} (0.6) n=64	242^{ab} (113) n=65	82^{b} (32) n=66	48^{a} (10) n=66	5.3^{a} (2.7) n=66	28^{a} (10) n=64	257^{b} (68) n=66	139^{b} (59) n=66

[abc] Two adjacent means that share the same superscript are not significantly different (P=0.05) using the Bonferroni multiple comparison method.
n=sample size.
NA=data not available.

The microbial quality of the Musi water is described in Table 7. The data presented was collected from June 2003 to May 2004. *E coli* load at the first sampling point is 7.78 Log_{10}(counts/100ml) and 4.7 Log_{10}(counts/100ml) at the location furthest downstream. This corresponds to an *E coli* removal of 99.9%. The decrease in *E coli* concentration between sampling point I and VII is statistically significant ($p<0.05$).

The egg concentration at the first sampling point is 170 eggs/l. At the last point the concentration is 0.1 eggs/l. This difference is statistically significant ($p<0.05$). The concentration of nematode eggs is significantly higher at points I and II compared to the remaining sampling points, while the decrease within these points is not statistically significant ($p>0.05$). The nematode egg removal is 99.9%.

The proportional distribution between *Ascaris lumbricoides* and hookworms change downstream. From being almost equal it switches to a higher occurrence of hookworms. All the eggs at sample point VII are identified as hookworm eggs.

Table 7 Concentrations of *E coli* and Total Nematodes along Musi River, downstream of Hyderabad. Average values with standard deviation in parentheses. The distribution of *Ascaris*, Hookworms and *Trichuris* expressed as percentage of Total Nematodes

Sampling point	*E coli* Log_{10}(counts/100ml)	Total Nematodes Eggs/l	%		
			Ascaris	Hookworm	Trichuris
I	7.78^{a} (0.75) n=4	170^{a} (111) n=18	54	43	3
II	7.03^{ab} (0.21) n=4	161^{a} (93) n=17	52[1]	44[1]	3[1]
III	6.64^{abc} (0.27) n=5	34^{b} (17) n=21	58	41	1
IV	5.77^{bcd} (0.79) n=3	7^{b} (5) n=14	22	71	7
V	5.63^{bcd} (0.97) n=4	2^{b} (2) n=15	22	64	14
VI	5.44^{bcd} (0.79) n=5	1^{b} (2) n=15	26	74	--
VII	4.7^{d} (0.83) n=6	0.1^{b} (0.3) n=17	--	100	--

[abcd] Two adjacent means that share the same superscript are not significantly different (P=0.05) using the Bonferroni multiple comparison method.
n=sample size.
[1] The percent do not add up to 100. This because *Enterobius vermicularis* is included in the Total Nematode concentration.

Water samples were on a few occasions collected when the flow was not measured. In Figure 17 those occasions are omitted to enable pair-wise comparison. The data presented is collected from August 2003 to May 2004. The flow, measured at point I, varies between 8 000 m^3/hour and 43 000 m^3/hour, with a mean flow of 25 000 m^3/hour (609 000 m^3/day). From December to March the flow tends to be lower than from April to September. Data is not available for June, July, October and November.

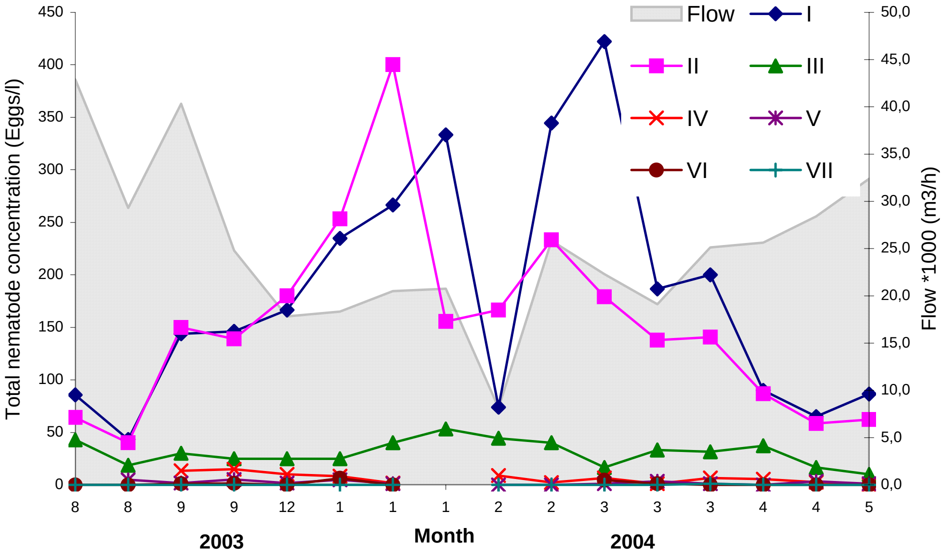

Figure 17 Variation in nematode concentrations at sampling point I - VII and flow, measured at point I, from August 2003 to May 2004**.**

The total nematode concentration ranges from 43 to 422 eggs/l at sampling point I, 10 to 44 eggs/l at point III and 0 to 1 egg/l at point VII. The variation is largest in sampling points I and II. At III one can still observe a fluctuation, but further downstream, where the average concentrations are small, the variation is smaller too. Concentrations seem to be higher between December and March, except at point I at one occasion in February 2004, when the nematode concentration was almost at the same level as at sampling point III.

The Musi River water was on a few occasions analysed for trace elements. The results are presented in Table 8 along with recommended maximum concentrations (NAS, 1972, Pratt, 1972). Point I was sampled in June 2002 and June 2003, II, IV and V were sampled twice in November 2002, III and VII four times, in June 2002 and 2003 and November 2003. VI was sampled three times, in June 2002 and 2003 and once in November 2003.

Table 8 Concentrations of trace elements interesting for crop production in the Musi River and phytotoxic threshold levels

Element	Musi River Concentration (mg/l)							Recommended[1] maximum concentration (mg/l)
	I	II	III	IV	V	VI	VII	
Aluminium (Al)	4.4	0.4	0.3	0.2	0.1	0.2	0.2	5.0
Arsenic (As)	0.10	0.00	0.02	0.01	0.00	0.02	0.02	0.10
Beryllium (Be)	NA	NA	NA	NA	NA	NA	NA	0.10
Cadmium (Cd)	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Cobalt (Co)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05
Chromium (Cr)	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.10
Copper (Cu)	0.14	0.02	0.02	0.01	0.01	0.01	0.00	0.20
Fluoride (F)	NA	NA	NA	NA	NA	NA	NA	1.0
Iron (Fe)	6.0	0.7	0.5	0.3	0.2	0.3	0.3	5.0
Lithium (Li)	NA	NA	NA	NA	NA	NA	NA	2.5
Manganese (Mn)	0.31	0.18	0.23	0.23	0.24	0.24	0.30	0.20
Molybdenum (Mo)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Nickel (Ni)	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.20
Lead (Pb)	0.2	0.0	0.0	0.0	0.0	0.0	0.0	5.0
Selenium (Se)	NA	NA	NA	NA	NA	NA	NA	0.02
Vanadium (V)	NA	NA	NA	NA	NA	NA	NA	0.10
Zinc (Zn)	0.3	0.1	0.0	0.0	0.0	0.0	0.0	2.0

NA: Data not available

[1] The maximum concentration is based on a water application rate that is consistent with good irrigation practices (10 000 m^3 per hectare per year).

Arsenic, Cadmium, Iron and Manganese are equal to or exceed the recommended maximum concentrations, but only at the first sampling location. Further downstream only Manganese exceeds the maximum concentrations. Aluminium and Copper show relatively high levels, but do not reach the maximum recommended.

5.2 RESERVOIR

The first of a series of weirs is at sampling location III where a reservoir is formed (Figure 18). The reservoir encompasses an area of 380 000 m^2 (38 ha).

The widths of the narrow and wide ends of the reservoir are 50 m and 152 m respectively, and the depths are estimated to 1 m and 6 m. The reservoir is assumed to stretch almost from sampling point II to point III (Figure 18). The length of the reservoir was measured to 4100 m. These estimates give a volume of approximately 1 283 000 m^3 using equation 7.

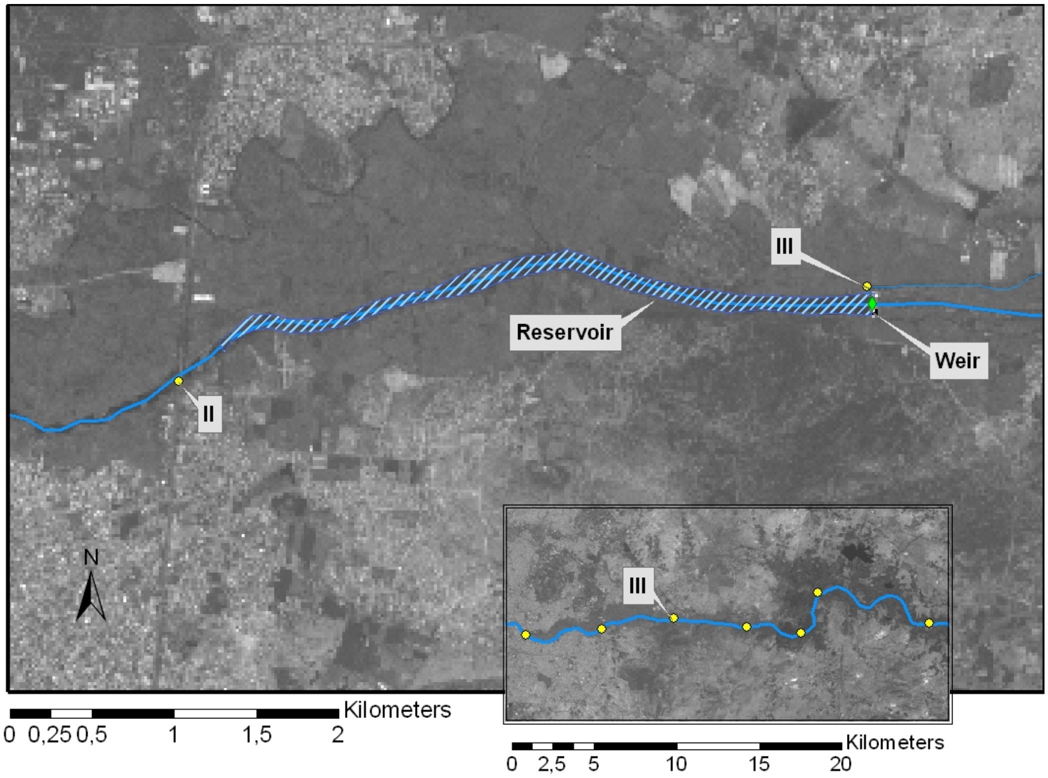

Figure 18 The reservoir area formed by the weir behind sampling point III. The reservoir encompasses an area of 38 ha. The distance between sampling point II and III is 4300 meters.

The water in the reservoir is turbid and smelly. A lot of rubbish as plastic bags, and water bottles accumulate together with floating grass and water hyacinth that are growing on the surface (Figure 19).

Figure 19 The weir forming the reservoir at sampling location III. Water hyacinth and floating grass is growing on the water surface.

5.2.1 Retention time

The flow used to calculate retention time was measured at sampling point I between August 2003 and September 2004. Where there were more than one measurement per month, a monthly average was calculated and from those values a yearly average flow value of 642 000 m^3/day was given. The rainfall on the reservoir was estimated to 928 m^3/day. Thus the total inflow is approximately 643 000 m^3/day.

Using the calculated volume and inflow, the retention time was estimated to 2 days (equation 1). The theoretical removal efficiencies and those measured are presented in table 9.

Table 9 Removal efficiencies in the reservoir at sampling point III, 9.6 km downstream Hyderabad

	Removal efficiency Measured (%)	Removal efficiency Theoretical[1] (%)
Intestinal Nematodes	79	77
E coli	57	93
BOD_5	56	44

[1] Using the estimated hydraulic retention time

Looking at the removal efficiencies for nematodes the estimated retention time of 2 days is very accurate. The theoretical removal efficiency agrees with the measured, and based on that the model can be used to estimate the overall retention time. By rearranging the terms in the model used to predict egg removal (Equation 8) and using the overall egg removal seen between sampling location I and VII (99.9%) the overall retention time from I to VII is estimated to 15.8 days.

Sediment samples were collected on one occasion in March 2004 at five different locations (Figure 20).

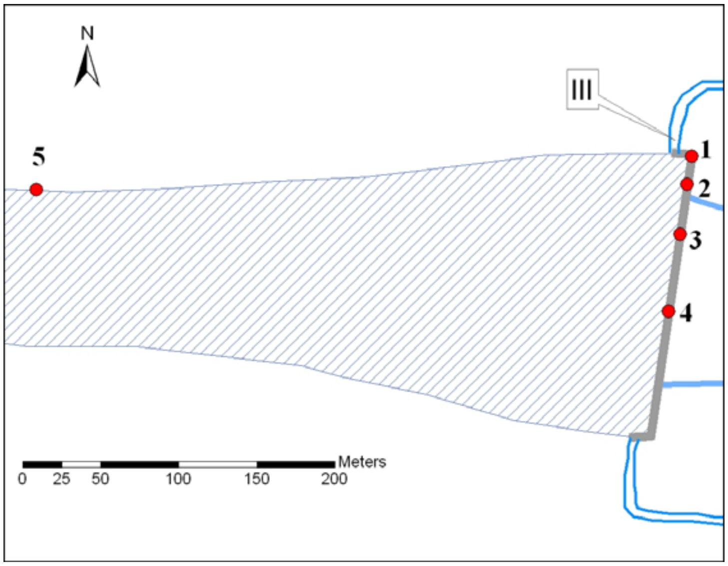

Figure 20 Locations of the sediment sampling points at III in the reservoir. 1 is located 0 m from the outlet to the canal. 2,3 and 4 are located 20, 50 and 100 m out on the weir. 5 is 420 m upstream from the weir.

The amount of eggs in the reservoir sediment is presented in Table 10. The concentration varies from 67 eggs/g dry weight (d.w.) at location 4, 100 m out on the weir, to 734 eggs/g d.w. at location 2, 20 m out on the weir. The highest value in water concentration corresponds to the lowest number of eggs in sediment. This is at location 4, 100 m out on the weir.

Table 10 Concentration of nematodes in reservoir sediment, expressed as eggs/g dry weight, and nematode concentration in reservoir water as eggs/l

Sampling location	Nematodes in sediments (eggs/g dw)	Nematodes in water (eggs/l)
1	477	40
2	734	33
3	417	20
4	67	167
5	235	2

5.3 IRRIGATION CANAL

From the first weir, at location III, irrigation canals are diverted (Figure 21). The north canal is shown on the map. The canal water was sampled on two occasions (February 2004) at four locations. The distance between IIIa and IIIb is 4000 m, IIIb and IIIc 700 m and between IIIc and IIId 2700 m. This gives a total distance of 7400 m. The average flow (measured in February and March 2004) is 280 000 m^3/day at IIIa and 115 000 m^3/day at IIId (Hytteborn, 2005).

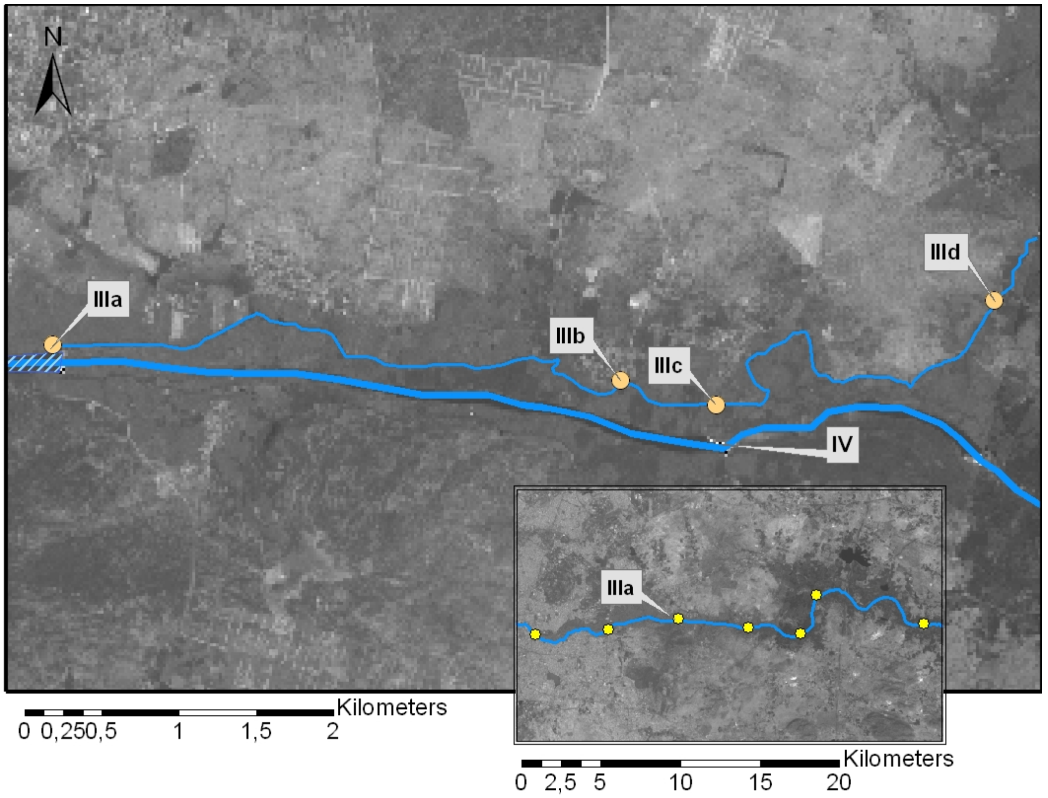

Figure 21 The north canal, diverted by the weir at sampling point III. The distance between IIIa and IIId is 7400 m.

The average nematode egg concentration in the irrigation canal ranges from 22 eggs/l to 61 eggs/l (Table 11). The concentration does not decrease downstream. The highest value is at the third sampling site, point IIIc. The BOD and the DO are also not following a pattern of increase or decrease, but for EC the trend suggests an increase in salt content. Eggs were found in the two dug wells: 222 eggs/l in the well at IIIc and 2 eggs/l in the well at IIId.

Table 11 Irrigation canal measurements. Average values with the range in parenthesis. Sample size in canal is two and in wells one.

Sampling location	Nematodes eggs/l	BOD_5 mg/l	DO mg/l	EC dS/m
III a	58 (53-63)	170 (134-206)	0.30 (0.25-0.34)	1.97 (1.95-1.99)
III b	42 (27-57)	126 (118-134)	0.17 (0.10-0.24)	2.01 (1.99-2.03)
III c	61 (33-89)	154 (124-183)	0.17 (0.09-0.24)	2.02 (2.00-2.04)
III d	22 (20-24)	145 (137-152)	0.22 (0.19-0.24)	2.04 (2.02-2.06)
Well c	222			
Well d	2			

6 DISCUSSION

6.1 WATER QUALITY

Looking at three out of nine constituents the water leaving Hyderabad in the Musi River would be classified as strong wastewater (Table 1). BOD levels at sampling point I lie above the medium category, and TDS and Chloride both exceed the strong category (Table 5 and Table 6). Data is not available for total solids, suspended solid, Nitrogen, Phosphorus, alkalinity or grease. It is not likely that knowledge of these parameters would change the classification. The sewage that is let into the Musi is not diluted as the actual river has dried up (except from monsoon season) and the water use in the city is low. The sewage tends to be less diluted in arid and semiarid climates, where the water use is low (Pescod, 1992).

Regarding trace elements toxicity to plants, there should be no hindrance to use the Musi water for irrigation as the only measured trace elements that exceed (or reach) the recommended maximum concentrations (for irrigation) at sample point I are Arsenic (0.10 mg/l), Cadmium (0.01 mg/l), Iron (6.0 mg/l) and Manganese (0.31) (Table 8). Further downstream only Manganese exceeds the threshold levels. Manganese exists in oxidising environments (in the presence of oxygen) as MnO_2 but will in mildly reducing conditions (anaerobic) dissolve to the Mn ion (Hounslow, 1995), which could explain the high levels of manganese.

The toxicity of Arsenic to plants varies widely. It is already toxic to rice at 0.05 mg/l (Pescod, 1992) but as the concentration exceeds that value only at sampling point I, and as there is no cultivation of rice in that particular area, Arsenic should not cause a problem. Cadmium is toxic to many plants at concentrations of 0.1 mg/l; the recommended concentration is lower due to Cadmiums potential to accumulate in soils and plants to concentrations that are harmful to humans. Iron is not toxic to plants in aerated soils but can contribute to soil acidification and loss of availability of some essential nutrients. Manganese is usually only toxic in acid soils (Pescod, 1992). Manganese should not affect plant growth as the soil pH in the area ranges from 7 to 9 (Ensink, 2005).

Aluminium and Copper show relatively high levels, close maximum concentrations. Aluminium causes non-productivity in acid soils, but in soils at pH > 7 the ion precipitate and the toxicity is eliminated. Copper is toxic to plants at 0.1 to 1.0 mg/l (Pescod, 1992).

Another possible problem with trace elements in irrigation water is the accumulation of trace elements in soil. Studies in Pakistan show no excess heavy metal accumulation in wastewater-irrigated soils (Van der Hoek *et al.*, 2002). Other studies (Singh *et al.*, 2004) in India show that soil irrigated with wastewater with less heavy metals than the Musi water have a much higher content of several trace elements than the control area.

With respect to the four problem categories; salinity, infiltration rate, specific ion toxicity and miscellaneous effects (Table 2), medium restrictions should be in place for use the Musi water for irrigation purposes. The farmers may possible experience some yield reductions (Ayers *et al.*, 1985).

Both the data from PCB and IWMI (Table 5 and Table 6) fall under the same category concerning salt content. There should be restrictions on using the water for irrigation purposes everywhere in the study area, except from upstream of Hyderabad where the salt content is relatively low (Table 6). The salt content tends to increase further downstream (see below).

As the SAR value ranges from 4.3 to 5.7 and EC exceeds 1.2 dS/m at all locations, the infiltration rate should not be affected (Ayers *et al.*, 1985), but as surface irrigation is practiced, a SAR value between 3 and 9 could mean that the sodium content is high enough to be toxic to plants. The same is valid for the Cl ions. After recalculations from mg/l to mmol_c/l, the chloride content ranges from 5.1 mmol_c/l to 7.2 mmol_c/l and could be toxic. Thus there are medium restrictions on use. None of the crops grown in the area would be classified as very sensitive to chloride toxicity but rice and spinach are considered semi-tolerant to sodium. Paragrass, however, is considered tolerant (Ayers *et al.*, 1985).

Upstream values of SAR, EC and Chloride concentration are 0.8, 0.3 dS/l and 1.34 mmolc/l respectively. This results in no restrictions on use concerning ion toxicity but medium restrictions concerning infiltration (Table 2). The SAR value upstream is low, but in relation with the low salt content (EC), it could mean that the Sodium content is high relative to other dissolved ions, which would cause soil particles to disperse and influence the infiltration rate.

After recalculation of the absolute nitrate (NO_3) values in Table 6 to express them in terms of nitrogen held as nitrate (NO_3-N), the values ranges from 1.86 mg/l to 2.16 mg/l. There is no restriction on use (Table 2). This is surprising, as wastewater is considered to be very high in nutrients. It is possible that the presented values are NO_3-N and not absolute NO_3 concentrations. If that is the case, the numbers that should be used for evaluation in Table 2 ranges from 8.2 mg/l to 9.9 mg/l, and medium restrictions would apply. The guidelines for interpretation of irrigation water quality are developed to suit all irrigation water sources. In fresh water streams the main nitrogen source is NO_3 originating from wastewater treatment effluents or from leakage from agriculture, but in untreated sewage nitrogen exists mainly as organic nitrogen or as NH_4. These two compounds can, in aerobic conditions, undergo a nitrification process whereupon NO_3 is formed. The plant available form is NO_3 but also the other forms are potential sources of nutrients. Thus, the nutrient content should be expressed as total nitrogen or as NO_3 and Kjeldahl-nitrogen (sum of organic nitrogen and NH_4-nitrogen). The water quality in the Musi River is monitored using parameters applicable to fresh water streams, not the heavily wastewater-polluted river the Musi has become. To get the full picture, more detailed measurements of nitrogen is needed.

Considering the PCB-classification of irrigation waters the Musi water is fit for use. The pH, EC and SAR are all below the maximum permissible values.

With the high organic load it is not surprising to find so little dissolved oxygen (Table 5). Bacteria consume oxygen when degrading the organic matter. The conditions are almost anaerobic, but at the last sampling point the dissolved oxygen reaches above 2 mg/l. Fish have been observed at this spot and the water is clearer (Figure 16). PCB reports oxygen levels as high as 7.2 mg/l upstream and 6.3 mg/l at sampling location

VII. As warm surface streams usually have a dissolved oxygen content of 3-5 mg/l (Hounslow, 1995), the measurements made by IWMI are more accurate than the PCB data.

6.2 CHANGE IN WATER QUALITY

There is a significant change in water quality between the upstream location and the locations downstream of Hyderabad (Table 6). This is not surprising as the Musi downstream of Hyderabad is no longer a natural river but consists only of domestic sewage. Most of the Na and Cl increase can be explained by the use of ordinary table salt for cooking. The organic material (here expressed as COD) is mainly human excrement, but also consists of hair, detergents and such. The increase in organic matter naturally gives rise to an increase of nutrients (NO_3 and PO_4). The absence of dissolved oxygen (Table 5) can also be explained by the increase in organic matter (as oxygen is consumed by decomposing bacteria). Concentrations of magnesium are not strongly influenced by anthropogenic activities, but are products of weathering of the earth's crust minerals. Therefore no increase is seen between the upstream location and the downstream locations as the magnesium was already present in the drinking water. SO_4, on the other hand, is influenced by human activities, such as combustion of coal and petroleum (Hounslow, 1995), and the increase in SO_4 levels can be explained by dry deposition of sulphur, or storm water run off from the highly polluted area of Hyderabad. Calcium is also a product of weathering and the difference between the upstream locations and downstream is not substantial. Calcium is present in the drinking water and supplied in foods and excreted in urine and faeces (Feachem *et al.*, 1983).

When looking at the change in water quality that takes place downstream of Hyderabad, both IWMI and PCB data will be considered (Table 5 and Table 6).

EC and TDS increase with the distance from the city. Due to evaporation of water and/or return flows from agriculture, dissolved ions accumulate. This accumulation can also be observed among the ions (Na, Cl, Ca and SO_4). Moreover, the increase in EC is observed along the irrigation canal (Table 11), although it is not verified statistically here.

The BOD and COD both decrease with the distance from Hyderabad. The overall removal is 86.9 and 62.3% for BOD and COD respectively. The main removal takes place in the reservoirs formed by the diversion weirs along the river where the water is still and coarse material settles. The conditions in the reservoir resemble anaerobic ponds in a WSP system. Over the first weir the BOD removal is 56%, but after that the removal is smaller. One reason could be that retention times in the following reservoirs are shorter and finer material cannot settle. As the conditions are anaerobic, no oxidation of dissolved organic matter can take place. Between the two last sampling points, the removal is 42%. Oxygen levels are now higher which means oxidation of non-settleable organic matter is possible. The flow is lower and there are three weirs located between sampling point VI and VII. Therefore even finer materials have a chance to settle. The BOD originating directly from sewage may be lower than shown, at least at point VII, where the fraction of particle organic matter should be small and algae can be observed. The BOD analysis is not performed on filtered samples and therefore the algae biomass can give false levels of BOD.

The theoretical BOD removal over the reservoir at point III (Table 9) based on an estimated retention time of 2 days is lower than the measured. This is a very rough estimate, and the model (Equation 11) is actually used in designing facultative ponds, not anaerobic (Pescod, 1992), and thus not applicable on the reservoir in this river, as the conditions are anaerobic.

No BOD removal is observed in the canal (Table 11). The water is flowing all throughout the canal system, and coarse material is not let to settle. With a surface velocity of approximately 0.6 m/s, the time to travel the distance between the first sampling point and the last (7400 m) is only 3.4 hours.

It is difficult to draw conclusions about the nitrogen status as only NO_3 is measured. It could be that neither nitrification nor denitrification takes place, and the NO_3 concentration remains stable. The main process in anaerobic ponds is ammonification, but denitrification is possible when NO_3 levels are high enough (Mara, 1997) under anaerobic conditions. In the deeper layers of the reservoir, the oxygen level ought to be lower than at the surface, and denitrification might occur here and reduce NO_3 to nitrogen gas. On the other hand, when the water is applied to land the nitrification process start and the NH_4 present is oxidises to NO_3. The very soluble molecule is returned to the water stream through agricultural leakage.

No removal of phosphate is observed along the river. Phosphor is removed by incorporation of inorganic phosphor to algal biomass that settles, and precipitation of inorganic phosphor that becomes immobilised in the sediments. But under anaerobic conditions, the rate of resolubilisation and mineralisation is greater than the rate of immobilisation and hence no removal of PO_4 is seen. In a WSP system, most of the phosphor occur place in maturation ponds with aerobic conditions (Mara, 1997).

A difference between the data from IWMI and that from PCB is noticeable. The EC and TDS values from IWMI suggest a slightly higher salinity. When considering the fact that COD usually is 3 times higher than BOD (VAV, 1996) the data from PCB is very low.

6.3 PATHOGENS

Both *E coli* and total nematode concentrations decrease by 99.9% between point I and VII (Table 7). In the case of the nematodes, this means that the WHO guideline for restricted and unrestricted irrigation is reached by point VI. There exists an excess risk of *Ascaris* infections in farm workers and their families at concentrations lower than the WHO guideline (Blumenthal, 2001). The effect is similar to exposure of raw wastewater (90-135 eggs/l). The prevalence of *Ascaris* infections (in age group 5-14 years) in areas irrigated with raw wastewater, wastewater treated to < 1 egg/l and rain fed areas were 12.4%, 8.4% and 1%, respectively. Habbari *et al.* (2000) report an Ascariasis prevalence of five times higher among school children in wastewater irrigated regions compared to control regions (20.5% and 3.8%, respectively). A study in Pakistan shows a higher prevalence of hookworm infections among wastewater farmers (van der Hoek *et al.*, 2002). One study, performed in a wastewater discharge area in Morocco (the wastewater not used for irrigation purposes) also shows a higher prevalence of *Ascaris* infections amongst school children living in the discharge area.

The prevalence was 18.1% and 1% for discharge area and control area respectively (Lamghari Moubarrad, 2005). The water quality in the Musi study area imposes an excess risk of helminth infections; not only to farm workers and their families, but also to inhabitants in Hyderabad living and working along the banks of the Musi River. On many places the banks are used as public toilets, which further contribute to disease spreading. In the case of *Ascaris*, Hookworms and *Trichuris,* the direct contact with wastewater should not be the most important factor, as these nematodes all need a soil development stage to become infective and little or no transmission is waterborne (Feacham *et al.*, 1983). The contact with soil contaminated with wastewater ought to be of higher importance. The prevalence of infections in children compared to adult farm workers (Blumenthal, 2001), is most probably due to the fact that children may neglect to wash their hands before eating, and that their lack of knowledge of the risks associated with wastewater contaminated soils.

A new guideline value of 0.1 eggs/litre is proposed as studies show that there exists an excess risk of nematode infection of consumers of wastewater irrigated crops, even at very low concentrations (Blumenthal, 2000). Ayers *et al.* (1992b) studied the level of contamination of lettuce spray irrigated with different quality waters. Irrigation with wastewater of WHO (1989) guideline quality (0.5 eggs/l) resulted in no intestinal nematode contamination of lettuce at harvest or very slight contamination of a few plants (6%). Crops irrigated with raw wastewater (>100 eggs/l) were contaminated with up to 60 eggs/plant. Irrigation with anaerobic pond effluent (>10 eggs/l) reduced the level of contamination to 0.6 eggs/plant. Rainfall or clean water irrigation prior to harvest reduced the contamination by 98%. Another study showed that surface irrigation with good quality wastewater (*Ascaris* concentration of <3 eggs/l), resulted in contamination of 50 % of mint and coriander plants with an average of 4.63 and 2.7 eggs/kg, respectively (Amahmid *et al.*, 1999). Ayers *et al.* (1992b) also investigated the development stage of eggs on the lettuce. No infective eggs were found. This implies that no recontamination (from soil) had occurred, but also that the contamination of crops unlikely contributes to helminth infections in consumers of wastewater irrigated crops. Again, the soil-transmitted helminths require soil with perfect moisture, temperature and oxygen levels to develop an infectious stage (Bogitsh, 1998). The greatest risk would be if crops were to be contaminated with infectious eggs from the soil. The infectious egg may stay viable in soil for many months, but should recontamination occur, the crops grown in the Musi area are eaten cooked, thus the risk for consumers should be minimal.

The seasonal variation (Figure 17) shows that the concentrations of nematode eggs are higher from December to March. These are months with dry weather, which means that the domestic wastewater is less diluted and the concentration higher. The mean egg concentration at sampling site I during dry season is 248 eggs/l compared to 94 eggs/l during rainy season. The risk of *Ascaris* infections is greater (children <5 years) in the dry season than during the rainy season (Blumenthal *et al.*, 2001). This is explained by the fact that the area (Mexico) is so dry that surviving *Ascaris* eggs are likely to be supported only in wastewater-irrigated areas. Better accesses to fresh water for hand washing could possible contribute further to these results.

Over the first weir the removal of total nematodes is 79% (Table 9). This is due to the stagnation of water in the reservoir. The estimate of a retention time of 2 days gave a theoretical removal of 77%. The model used to predict the removal (Equation 8) is based only on retention time. This is the single most important factor for removing eggs. To achieve a 99.9% removal, a retention time of 16 days would be required (rearrangement of Equation 8). Amahmid *et al.* (2002) report a 100% removal in only 9.5 days (influent concentration 1.7 eggs/l) in one stabilisation pond. A total of 20 days in a well-designed WSP-system would remove 100% of the Ascaris eggs (Feachem *et al.*, 1983). In an anaerobic pond with the hydraulic retention time of 10 h and an initial concentration of 158 eggs/l, the removal was only 26.6% (Ayers *et al.*, 1993).

No removal of nematodes where seen in running water (between point I and II and in the canal) (Table 7 and Table 11). It was surprising to find eggs in the wells, as the water should have been filtered through the canal wall. The concentration in well c was as high as 222 eggs/l. The high concentration might be due to resuspension of settled eggs as farmers were pumping water at the time of sampling. This reflects the situation when farmers are applying water to the fields and the result from well c is more accurate than from well d, where the water was still.

The concentration of nematodes in the sludge/sediment collected in the reservoir ranges from 67 eggs/g d.w. to 734 eggs/g d.w. (Table 10). The values are uncertain as only one sample on every location was analysed. The flow in the reservoir is most certainly not uniform, but water slows down on the sides and is more rapid in the centre. The concentration of eggs in sediment is at is lowest 100 metres out on the weir. This corresponds to the highest egg concentration in water. At the other sampling locations where water concentrations ranges from 20 eggs/l to 40 eggs/l, the sediment contains more eggs. The lowest water concentration was found on the upstream location. The water was still and all eggs hence had time to settle. Amahmid *et al.* (2002) counted *Ascaris* eggs in the sludge of a sedimentation pond with influent quality of 1.7 eggs/l, and found an average concentration of 7.1 eggs/g d.w.. The eggs in the sludge do not impose a risk, unless flooding occur and resuspended eggs are applied to soil. The *Ascaris lumbricoides* egg is heavier and thus settles more rapidly. The settling velocity of *Ascaris*, *Trichuris* and hookworms are 20 mm/min, 16 mm/min and 6 mm/min respectively (Ayers *et al.*, 1996). A switch in the distribution of eggs can be seen (Table 7). The *Ascaris*:hookworm ratio is at first close to one but after sampling location IV, the hookworms are overrepresented.

In this study *E coli* counts are measured instead of faecal coliforms. As discussed above, *E coli* is one of many faecal coliforms, and the most common. A 3-log removal of *E coli* is observed through the river system (Table 7). This corresponds to a total removal of 99.9%. Still, the WHO guideline of $< 10^3$ feacal coliform bacteria per 100 ml for unrestricted irrigation is not met. The final concentration is $10^{4.7}$ *E coli*/100 ml. The high content of *E coli* implies that there is a possibility that enteric pathogens, as *Salmonella*, *Shigella* and viruses are present. Blumenthal *et al.* (2001) studied (Mexico) the effect of exposure to untreated wastewater, with 10^7 faecal coliforms/100ml, on self-reported history of diarrhoeal disease. The study shows a higher risk of infection when exposed to untreated wastewater. When the quality was 10^3/100ml the exposure did not contribute to higher risk of diarrhoeal disease. Another study (Nigeria) also showed that users of irrigation water of 10^7-10^8 faecal coliforms/100ml had higher incidence of diarrhoea and typhoid fever compared to nonusers (Agunwamba, 2001). There exists an excess risk to diarrhoeal diseases related to contact to wastewater but as many of the infectious agents are endemic in many areas in developing countries, big outbreaks due to contamination of food crops are seldom seen. In Jerusalem cholera is not endemic and sanitation standards are high. This made the big cholera outbreak in 1970 possible (Fattal *et al.*, 1986). The above ranking of pathogens applies to developing countries; in developed countries the main negative health effects resulting from wastewater irrigation are associated with bacterial, protozoan and viral diseases.

The enteric pathogens are quite persistent in soil under optimal conditions. Faecal coliforms and *Salmonella* spp may survive many months, but in warm, dry climates the survival is usually less than 20 days and *Vibrio cholerae* usually survives less than 10 days in soil. The survival times for enteric pathogens on crops are relatively short as they are very sensitive to light, heat and to dry conditions. At temperatures of 20-30°C the usual survival times, on crops, are less than 15 days for faecal coliforms and *Salmonella* spp. *Shigella* spp and *Vibrio cholerae* usually survive less than 5 and 2 days respectively (Feachem *et al.*, 1986).

As seen before the wastewater is less diluted during the dry season (Figure 17). Blumenthal *et al.* (2001) reports a seasonal variation of self reported diarrhoeal diseases. The effect of exposure to untreated wastewater in the dry season was both stronger and more significant. During the rainy season the farmers do not have to irrigate as frequently and therefore the contact with wastewater is reduced and access to clean water for hand washing helps improve hygiene. Furthermore, heavy rains may cause leakage of pathogens on the surface to the deeper layers, thus reducing the contact with pathogens in soil. However, rates of diarrhoeal diseases increase during the rainy season (Blumenthal *et al.*, 2001). Rainfall can result in pathogen spread by runoff or by leaching through soil profile and bacterial and viral groundwater contamination increases during heavy rainfalls (Santamaría *et al.*, 2003).

The removal of *E coli* over the first reservoir was 44% (Table 9). The theoretical *E coli* removal, calculated with the estimated retention time of two days, is much higher than the measured removal. This can be explained by that the model used, to predict removal here is based on retention time and temperature, but faecal coliform removal is dependent on many other factors (Mara 1997, Davies-Colley *et al.,* 1999). Most of the faecal coliform removal in a WSP system occurs in the aerobic maturation ponds, where it is not unusual for the pH to reach 9 or more (Mara 1997). The rise in pH is due to rapid photosynthesis by pond algae, which consume CO_2. The bacteria die-off increases[6] with the pH. Another important factor for inactivation of bacteria is sunlight and studies show that high levels of DO enhance the effect (Davies-Colley *et al.*, 1999). As DO levels in the reservoir are low and the water turbid the sunlight will not reach the deeper layers of the reservoir.

In many of the areas where wastewater irrigation is performed the activity is indirect and uncontrolled, and it is not only the farm workers that come in contact with the wastewater. The disposal of sewage to water bodies, due to inadequate sanitation, have led to that a growing number of farmers have access to water around the year. But the poor sanitary conditions also expose non-farmers to pathogens and other hazardous elements. 7% of all deaths in 1990 were caused by poor water supplies and sanitation; this is the second largest cause of death. Only malnutrition was larger with

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[6] With the exception of *Vibrio cholerae* which grow at pH 8.5-9.5 (Jawetz *et al.,* 1991)

15% (Murray *et al.*, 2002). Diarrhoeal diseases are the 7th largest cause (2000) with 3.1% of all deaths in the world. Almost all of them occur in the so-called developing high mortality countries. For children below 5 years the number is 13.2%. With a total number of deaths for children under 5 years of 10.5 million (98% in developing countries) approximately 1.4 million children die every year, because of insufficient sanitary conditions (Mathers *et al.*, 2003).

In the state of Andhra Pradesh 7 million people in rural areas are using dangerously contaminated water. Of those, 65% are affected by water contaminated with bacteria. In Andhra Pradesh diseases caused by poor water supply and sanitation accounts for 11.3% of the total diseases. A seasonal variation of the prevalence of diarrhoea has been noted in the State (PCB, 2003). In the pre-monsoon, due to lack of water and during the monsoon peak, due to contamination of drinking water sources when sewers and latrines overflow.

To reduce health risks associated with wastewater irrigation, drip irrigation is an often-proposed measure for reducing water-crop and water-farmer contact. Drip irrigation is also a favourable technique to use in water scarce, hot regions as it reduces evaporation losses. Untreated wastewater is rich in suspended solids and this will cause clogging of the emitters (Pescod, 1992), thus very high quality wastewaters are required.

It is seen that the stagnation of the river water in reservoirs improves the quality and one measure could be to further excavate and increase reservoir volume and thus retention time. If more of the coarse material had time to settle in the first reservoir the BOD would decrease allowing oxygen levels to rise and, hence faecal coliform decay speed up. The water up to sampling point III (9.6 km downstream Hyderabad), and probably a bit further, would still be considered unsuitable for unrestricted irrigation but the water quality would improve more rapidly and making safe unrestricted irrigation feasible closer to Hyderabad. If then the effluent would be clear enough drip irrigation could be made possible. This would reduce water consumption and preventing the river from drying enabling irrigation further downstream.

One problem with using the reservoirs as sedimentation ponds is just, the sediment, or sludge, produced. If not well maintained, the volume decreases, and so will the effectiveness of the reservoir. Dredging would improve the capacity of the reservoirs.

Many of the results are built on assumptions. The estimate of the reservoir volume is very rough. To get more accurate results from flow measurements the velocity should have been measured at several segments of the cross section. This was not practicable as it is not safe to enter the river and no sophisticated equipment for velocity measurements was available. The float method can be used when high accuracy is not required or when costly installations are not warranted.

The *E coli* and the nematode egg concentration vary a lot within a sampling point between sampling occasions. The change in water quality between some of the sampling points is not significant due to high standard deviations. Fewer sampling locations and an average value from more than one sample (preferably three) would give more significant results

The Bonferroni multi comparison method was chosen to reduce the risk of making Type I errors. Consequently, the risk of making Type II errors increases. In other words, there is a possibility that there exists a difference in water quality where it is said to be none.

7 CONCLUSIONS

The Musi River is heavily contaminated with domestic sewage but for farmers it is a valuable resource providing irrigation water around the year. The irrigation infrastructure, built to divert irrigation water canals, helps to improve water quality. The main results of this master thesis is summarised below:

- The water in the Musi River can be classified as strong wastewater
- The discharge flow of wastewater from Hyderabad is at an average 642 000 m^3/day
- The first reservoir encompasses an area of 38 ha, a volume of 1 283 000 m^3 and an average retention time of 2 days
- The overall retention time in the reservoirs along the 27.8 km is approximately 16 days
- The irrigation infrastructure has an impact on water quality. BOD, intestinal nematode eggs and *E coli* concentrations significantly decreases downstream.
- The total removal of BOD, *E coli* and nematodes is 86.9%, 99.9% and 99.9% respectively
- Over the first reservoir the removal of nematodes, BOD and *E coli* is 79-, 56- and 57% respectively
- The salinity increases downstream, probably due to evaporation and agricultural return flows
- No BOD or nematode egg removal is seen along the irrigation canal. An increase in salt concentration can be seen
- The wastewater is less diluted during the dry seasons
- Due to the fact that *Ascaris lumbricoides* eggs are heavier than hookworm eggs the *Ascaris* eggs are removed at a earlier stage
- Trace element concentrations in Musi River do not impose a threat to crop production although there exists a possibility of accumulation in soil
- Medium restrictions on use should be held due to high salinity of the irrigation water
- More detailed measurements of nitrogen compounds is needed to be able to say anything about nutrient content
- The WHO guideline of 1 nematode egg per litre is reached 20.7 km downstream of Hyderabad

- The 99.9% removal of *E coli* is not enough to reach the WHO guideline of 10^3 faecal coliforms per 100 ml

- From literature studies conclusions can be made that there exists an excess risk of intestinal nematode- and enteric infections for farmers in the study area

- The Musi River is also a sanitary inconvenience to non-farmers working and living along its banks

- The reservoirs, within the study area, resemble anaerobic ponds in a Wastewater Stabilisation Pond system

8 REFERENCES

Alestig K. *Mask-diagnostik Mask-symtomatologi Mask-behandling*. Infektionskliniken, Östra Sjukhuset, Göteborg, Sweden. Jansen Pharma AB

Amahmid O., Asmama S., Bouhoum K., 1999. The effect of wastewater reuse in irrigation on contamination level of food crops by *Giardia* cysts and *Ascaris* eggs. *International Journal of Food Microbiology*, Vol 49, pp 19-26

Amahmid O., Asmama S., Bouhoum K., 2002. Urban wastewater treatment in stabilization ponds: occurrence and removal of pahoghens. *Urban Water* Vol. 4 pp. 255-262

Agunwamba J.C., 2001. Analysis of Socioeconomic and Environmental Impacts on Waste Stabilization Pond and Unrestricted Wastewater Irrigation: Interface with Maintenance. *Environmental Management* Vol. 27, No. 3, pp. 463-476

Ayers R.S., Westcot C.W., 1985. Reprinted 1994. *Water Quality for Agriculture - FAO irrigation and drainage paper 29*. Food and Agricultural Organisation of the United Nations, Rome. ISBN 92-5-102263-1

Ayers R.M., Alabaster G.P, Mara D.D, Lee D.L. 1992, A design equation for human intestinal nematode removal in waste stabilization ponds. *Water Research*, Vol. 26 No. 6, pp. 863-865

Ayers R.M., Stott R., Lee D.L., Mara D.D., Silva S.A., 1992b, Contamination of lettuces with nematode eggs by spray irrigation with treated and untreated wastewater. *Water, Science and Technology* Vol. 26 No 7-8 pp 1615-1623

Ayers R.M., Mara D.D., Lee D.L., Thitai W.N., 1993. Monitoring full scale waste stabilization pond in Kenya for nematode egg removal. *Environmental Technology,* Vol. 14, pp 295-300

Ayres R.M., Mara D.D., 1996. *Analysis of wastewater for use in agriculture; a laboratory manual of parasitological and bacteriological techniques*. World Health Organisation, Geneva, Switzerland.

Bartam J., Lewis K., Lenton R., Wright A., 2005. Focusing on improved water and sanitation for health. *The Lancet* Vol 365, pp 810-812

Blumenthal U.J., Peasey A., Ruiz-Palacios G., Mara D.D., 2000. *Guidelines for wastewater reuse in agriculture and aquaculture: recommended revision based on new research evidence. Task No: 68, Part 1.* Water and Environmental Health at London and Loughborogh, WELL

Blumenthal U.J., Cifuentes E., Bennett S., Quigley M.; Ruiz-Palacios G., 2001. The risk of enteric infections associated with wastewater reuse: the effect of season and degree of storage of wastewater. *Transactions of the Royal Society of Tropical Medicine and Hygiene* Vol 95. pp 131-137

Bogitsh B.J., Cheng T.C., 1998, *Human Parasitology*, Second editon, Academic Press. ISBN 0-12-110870-8

Buechler S., Devi G., Raschid L., 2002. Livelihoods and wastewater irrigated agriculture along the Musi river in Hyderabad city, Andhra Pradesh, India. *Urban Agriculture*, December 14-17.

Davie T., 2003. *Fundamentals of Hydrology*, Routledge, London, England. ISBN 0-415-22028-9

Davies-Colley R.J., Donnison A.M., Speed D.J., Ross C.M., Nagels J.W., 1999. Inactivation of Faecal Indicator Microorganisms in Waste Stabilisation Ponds: Interactions of Environmental Factors with Sunlight. *Water Research* Vol 33, No 5, pp 1220-1230

Dixo N.G.H., Gambrill M.P., Catunda P.F.C., van Haandel A.C. 1995. Removal of Pathogenic Organisms from the Effluent of an Upflow Anaerobic Digester using Waste Stabilization Ponds. *Water Science Technology* Vol 31 No 12 pp 275-284

Ensink J.H.J., 2003. *Wastewater use in agriculture in India; the role of irrigation infrastructure in health risk reduction*. unpublished PhD proposal

Ensink J.H.J., 2005. Personal communication

Fattal B., Yekutiel P., Shuval H.I., 1986. *Cholera Outbreak in Jerusalem 1970 Revisited: The Case for Transmission by Wastewater Irrigated Vegetables*. Environmental Epidemiology: epidemiological investigation of community environmental health problems. Ed Goldsmith, J.R. CRC Press chapter3, 49-59

Fattal B.; Lampert Y., Shuval H.I., 2004. *A Fresh Look at Microbial Guidlines for Wastewater irrigation in Agriculture: A Risk-assessment an Cost-effectiveness Approach.* Wastewater Use in Irrigated Agriculture. ISBN 92-90-90-5506

Feachem R.G., Bradley D.J., Garelick H. and Mara D.D. 1983. *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. Chichester: John Wiley and Sons World Bank Report No.11616

Field J., 2003. *Anaerobic Granular Sludge Bed Reactor Technology*. www.uasb.org/discover/agsb.htm#uasb (accessed January 2005)

Friedler E., 2001. Water reuse – an integral part of water resources management: Israel as a case study. *Water Policy* 3 pp 29-39

Gunnerson C.D., Shuval H.I., Arlosoroff S., 1985. Health Effects of Wastewater Irrigation and Their Control in Developing Countries. *Future of Water Reuse* Denver: AWWA Research

Habbari K., Tifnouti A., Bitton G., Mandil A., 2000. Geohelminthic infections associated with raw wastewater reuse for agricultral purposes in Beni-Mellal, Morocco. *Parasitology International* Vol 48, pp 249-254

HMWSSB, Hyderabad Metropolitan Water Supply & Sewage Board, 2005. *Musi River Conservation Project.* www.hyderabadwater.gov.in/ (accessed March 8 2005)

Hounslow A.W., 1995. *Water Quality Data: analyses and interpretation.* Lewis Publisher, CRC Press Inc, Boca Raton, Florida, USA. ISBN 0-87371-676-0

Hytteborn J., 2005. *Irrigation with wastewater in Andhra Pradesh, India, a water balance evaluation along Peerzadiguda canal* Master thesis, Swedish University for Agricultural Sciences.

ICRISAT, International Crops Research Institute for the Semi-Arid Tropics, 2004. Intranet, accessed February 2004

International Water Management Institute, 2000. *Projected Water Scarcity in 2025.* www.iwmi.cgiar.org/home/wsmap.htm#A1 (accessed March 6 2005)

Iwarson S. 1991. *Infektionssjukdommar*. Third edition. Almquist & Wiksell. ISBN 87-7749-052-5. Sweden

James L.G., 1988. *Principles of farm irrigation.* John Wiley & sons, Inc. ISBN 0-471-83954-X, USA

Jawetz, Melnik, Adelberg, Brooks, Butel, Ornston 1991, *Medical Microbiology*, Nineteenth edition, Appleton and Lange, ISBN 0-8385-6309-0

Johnson R.A., 2000. *Miller & Freund's Probability and Statistics for Engineers.* Sixth edition, Prentice-Hall, Inc. ISBN 0-13-014158-5

Lamghari Moubarrad F.Z., Assobhei O., 2005, Impact of urban effluents on intestinal helminth infections in the wastewater discharge zone of the city of El Jadida, Morocco. *Management of Environmental Quality: An International Journal* Vol. 16 No. 1 pp 6-16

Mara D.D., 1994. Wastewater treatment and reuse in agriculture. *New World Water* pp. 107-109

Mara D.D 1997, Design Manual for Waste stabilization ponds in India. Tropical Public Health Engineering www.leeds.ac.uk/civil/ceri/water/tphe/publicat/pdm/india/india.html (accessed December 2004)

Mara D.D, 2001. Appropriate wastewater collection, treatment and reuse in developing countries. *Municipal Engineer* 145, Issue 4 pp 299-303

Marias G.v.R., 1974. Faecal bacterial kinetics in waste stabilisation ponds. *Journal of the Environmental Engineering Division, American Society of Civil Engineers.* Vol 100 (EE1), pp 119-139

Mathers C. D., Bernard C, Moesgaard Iburg K, Inoue M, Fat D. M, Shibuya K, Stein C, Tomijima N, Xu H. 2003. *Global burden of disease in 2002: data sources, methods and results*. Global Programme on health policy discussion Paper No. 54, World Health Organisation

McGarry M.G., Pescod M.B., 1970. *Stabilisation pond design criteria for tropical Asia.* Proc. 2nd International Symposium on Waste Treatment Lagoons, Kansas City. pp 15-46

Meiring P.G., Drews R.J., van Eck H., Stander G.J. 1968. A guide to the use of pond systems in South Africa for the purification of raw and partially treated sewage. CSIR Special Report WAT34. National Institute for Water Research, Pretoria.

Murray C.J.D, Lopez A. D., 1996 *The Global Burden of Disease.* Harvard University press, Cambridge, MA

NAS, National Academy of Sciences and National Academy of Engineering, 1972. Water Quality Criteria. US Environmental Protection Agency, Washington DC. Report No. EPA-R373-033. pp 592

Parr J., 2005. Review of anaerobic treatment processes (for developing countries). Water and Environmental Health at London and Loughborogh. www.lboro.ac.uk/well/resources/fact-sheets/fact-sheets-htm/ratp.htm (accessed February 27 2005)

Parr J, Smith M, Shaw R 1999. Technical Report No 64 Wastewater treatment options. Water and Environmental Health at London and Loughborogh (WELL)

PCB, Pollution Control Board, Andhra Pradesh 2003, *State of the Environment of Andhra Pradesh*, www.appcb.org (accessed March 2 2005)

Pearson H.W., Mara D.D., Smallman D.J., Mills S., 1987. Physiochemical parameters influencing faecal coliform survival in waste stabilisation ponds. *Water science and technology.* Vol 19. No 12. pp 145-152

Peña M.R., Rodriguéz J., Mara D.D., Sepulveda M., 2000. UASB or anaerobic ponds in warm climates? A preliminary answer from Colombia. *Water science and technology.* Vol 42 No 10 pp 59-65

Pescod M.B., 1992. *Wastewater treatment and use in agriculture – FAO irrigation and drainage paper 47*. Food and Agricultural Organisation of the United Nations, Rome. ISBN 92-5-103135-5

Pratt P.F., 1972. Quality criteria for trace elements in irrigation waters. California Agricultural Experiment Station. pp 46

Reddy M. 2004. Amberpet Sewage Treatment Plant, Hyderabad. Personal communication, March 3 2004.

Santamaría J., Toranzos G.A., 2003. Enteric pathogens and soil: a short review. *International microbiology* Vol.6 pp 5-9

Shuval H.I., Adin A., Fattal B., Rawitz E., Yekutiel P., 1986. *Wastewater Irrigation in Developing Countries: Health effects and technical solutions*. Summary of World Band Technical Paper No. 51. Integrated Resource Recovery Series GLO/80/004 Number 6. The World Bank. Washington, DC, USA

Singh K.P., Mohan D., Sinha S., Dalwani R., 2004. Impact assessment of treated/untreated wastewater toxicants discharged by sewage treatment plans on health, agricultural and environmental quality in the wastewater disposal area. *Chemosphere* No 55 pp 227.255

UN Department of Technical Cooperation for Development. 1985. The use of non-conventional water resources in developing countries. Natural Water Resources Series No 14. United Nations DTCD, New York.

UN Department of Economic and Social Affairs, 2001. *World Urbanization Prospects: The 2001 Revision*. www.un.org/esa/population/publications/wup2001/WUP2001report.htm#top (accessed March 8 2005)

U.S. Bureau of Reclamation, *Water Measurement Manual* (1975), Department of the Interior, U.S. Government Printing Office, Washington, D.C., 327 pp.

USEPA/USAID (United States Environmental Protection Agency/United States Agency for International Development). 1992. *Guidelines for Water Reuse United States Environmental Protection Agency (Technical Report no. 81),* Washington, DC, 252 pp

Van der Hoek W., Hassan M.U., Ensink J.H.J., Feenstra S., Raschid-Sally L., Munir S., Aslam R., Ali N., Hussain R., Matsuno Y., 2002. *Urban Wastewater: A Valuable Resource for Agriculture – A Case Study from Haroonabad, Pakistan*. Research Report 63. Colombo, Sri Lanka: International Water Management Institute.

VAV (Svenska Vatten och Avloppsverksföreningen) och Svenska Kommunalförbundet 1996. *Introduktion till Avloppstekniken.* Kommentus förlag, Stockholm. ISBN 91-7099-542-7

Weisstein E.W., "Bonferroni Correction." From *MathWorld*--A Wolfram Web Resource. http://mathworld.wolfram.com/BonferroniCorrection.html. (accessed February 17 2005)

WHO Scientific Group (1989) *Health guidelines for the use of wastewater in agriculture and aquaculture.* Executive summary of Technical Report Series 778, World Health Organisation, Geneva.

World Health Organization, 1996. *Water Quality Monitoring - A Practical Guide to the Design and Implementation of Freshwater Quality Studies and Monitoring Programmes.* www.who.int/docstore/water_sanitation_health/wqmonitor/ch09.htm (accessed March 6 2005)

World Health Organization, 2003. Worm control, Newsletter Issue 1. March 2003. http://www.who.int/wormcontrol/newsletter/en/ (accessed February 2005)