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Institute for Integrated Management
of Material Fluxes and of Resources

SAFE USE OF WASTEWATER IN AGRICULTURE: GOOD PRACTICE EXAMPLES

Hiroshan Hettiarachchi
Reza Ardakanian, Editors

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PREFACE

Population growth, rapid urbanisation, more water intense consumption patterns and climate change are intensifying the pressure on freshwater resources. The increasing scarcity of water, combined with other factors such as energy and fertilizers, is driving millions of farmers and other entrepreneurs to make use of wastewater. Wastewater reuse is an excellent example that naturally explains the importance of integrated management of water, soil and waste, which we define as the Nexus approach. The process begins in the waste sector, but the selection of the correct management model can make it relevant and important to the water and soil as well. Over 20 million hectares of land are currently known to be irrigated with wastewater. This is interesting, but the alarming fact is that a greater percentage of this practice is not based on any scientific criterion that ensures the "safe use" of wastewater. In order to address the technical, institutional, and policy challenges of safe water reuse, developing countries and countries in transition need clear institutional arrangements and more skilled human resources, with a sound understanding of the opportunities and potential risks of wastewater use.

In 2011 seven UN-Water members, partners and programmes led by the UN-Water Decade Programme on Capacity Development (UNW-DPC) joined efforts to address the capacity needs of countries with regards to the Safe Use of Wastewater in Agriculture (SUWA). The Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), the United Nations Environment Program (UNEP), the United Nations University Institute for Water, Environment and Health (UNU-INWEH), the International Water Management Institute (IWMI), and the International Commission on Irrigation and Drainage (ICID) were the other six partners. Between 2011 and 2013, these capacity development activities brought together 160 representatives from 73 UN member states from Asia, Africa, and Latin America. Further support in these fields and the continuation of the SUWA initiative were strongly requested by the participants during these activities. With the formal cessation of UNW-DPC in 2015, the coordination of the SUWA initiative was transferred to the United Nations University. Currently the United Nations University Institute for Integrated Management of Material Fluxes and of Resources (UNU-FLORES) and UNU-INWEH are responsible for coordinating SUWA activities together with other partners.

The current phase of SUWA aims to support UN member states in developing their national capacities in focus areas identified and prioritised during 2011–2015, promoting the safer and more productive use of wastewater. Developing countries and countries in transition remain to be the focus. Sharing information between countries/regions on "good practice examples of safe water reuse in agriculture" is one of the important objectives identified during the early phase of the SUWA initiative. In support of accomplishing this objective, UNU-FLORES identified several interesting case studies from around the world in 2015. Many of them were also orally presented and discussed at the workshop organised by UNU-FLORES in Lima, Peru, in February 2016. This book includes 17 such case studies selected from Latin America, Asia, and Africa. For ease of navigation through the content, the material is presented in three sections; Section I: Technological Advances; Section II: Health & Environmental Aspects; and Section III: Policy & Implementation Issues. We sincerely hope the content of this book will enhance knowledge sharing between the regions and also help us learn from each other.

We wish to thank the authors of the case studies for their hard work in sharing their knowledge as well as for the roles they played as peer reviewers. Special thanks also go to our own colleagues at UNU-FLORES, including Mr. Arjun Avasthy and Ms. Serena Caucci for their tireless contribution. Last but not least, we would like to offer our sincere gratitude to the German Federal Ministry for Economic Cooperation and Development (BMZ) for the generous financial support we received to make this project a reality.

Hiroshan Hettiarachchi
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CASE 1

Managed Aquifer Recharge Systems for Natural and Sustainable Wastewater Reclamation and Reuse Technology: Health Concerns Associated with Human Viruses (USA)

Walter Q. Betancourt, Ian L. Pepper, and Charles P. Gerba[1]

Abstract

Managed aquifer recharge (MAR) systems such as riverbank filtration and soil-aquifer treatment all involve the use of natural subsurface systems to improve the quality of recharged water (i.e., surface water, storm water, reclaimed water) before reuse (e.g. planned potable reuse). During MAR, water is either infiltrated via basins, subsurface injected or abstracted from wells adjacent to rivers. MAR systems represent an attractive option for augmenting and improving groundwater quality as well as for environmental management purposes. However, reuse systems designed for applications that involve human contact should include redundant barriers for pathogens that cause waterborne diseases. This case covers key aspects of a case study on virus removal at three full-scale MAR systems located in different regions of the United States (Arizona, Colorado, and California). MAR projects may be economically viable for developing countries; however, sustainable management is relevant to successfully maintain the attributes necessary for potable and non-potable water reuse.

Keywords: management, aquifer, recharge, removal, viruses

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1. Introduction

Increased water demand and supply in the world coupled with contamination of surface and ground water, uneven distribution and pressure on limited available water resources plus frequent droughts caused by extreme global weather patterns, has placed additional demand on the promotion for innovative sources of water supply and local conservation. In this context, high quality effluents derived from wastewater treatment and reclamation technologies are being increasingly used in many countries (e.g. United States, Australia, Germany, Saudi Arabia, The Netherlands) for indirect potable (i.e. replenishment of groundwater resources) and non-potable (i.e., agricultural and landscape irrigation) reuse purposes (Clinton 2007; Dillon et al. 2009; Alidina et al. 2015).

Planned indirect potable use is a careful and deliberate process to augment water resources while maintaining health and environmental safeguards. Most planned indirect potable reuse is linked to groundwater recharge. However, most indirect potable reuse in practice, whether it is planned or unplanned, occurs through blending with surface water (Asano 2007). Groundwater recharge with reclaimed water is an approach to water reuse that results in the augmentation of groundwater for various beneficial uses, including municipal water supply, agricultural irrigation, and industrial water supply. Groundwater recharge has been used to (i) reduce, stop, or even reverse declines of groundwater levels, (ii) protect underground freshwater in coastal aquifers against saltwater and brackish water intrusion; and (iii) store surface water, including storm water or other surplus water and reclaimed water for future use; (iv) to negate potential problems of land subsidence (Asano, 2007). In the United States, groundwater recharge with reclaimed water has been practiced for both non-potable and indirect potable reuse applications since the 1960s. The major advantage of subsurface storage is the potential improvement in water quality that occurs during the groundwater recharge process. Unlike subsurface storage, surface storage with reclaimed water can result in a significant deterioration of water quality from secondary contamination and from algal blooms (Asano 2007).

Managed aquifer recharge (MAR) including riverbank filtration (RBF), soil aquifer treatment (SAT) and aquifer recharge and recover (ARR) provides a natural and sustainable wastewater reclamation and reuse technology that can renovate wastewater effluents to drinking water levels, and thus represents an important component for indirect potable reuse supply (Asano and Cotruvo 2004; Dillon et al. 2009; Missimer et al. 2011; Bekele et al. 2011). During MAR, the water is either infiltrated via basins, subsurface injected or abstracted from wells adjacent to rivers.

The quality of the source water (e.g. storm water, impacted surface water or natural streams, properly treated municipal or industrial wastewater) can improve during infiltration and subsurface soil passage (Sharma and Amy 2011). Microbial pathogens, nutrients and many of the chemical contaminants are either removed or biotransformed (Weiss et al. 2005; Pang, 2009; Hoppe-Jones et al. 2010). In regions where conventional freshwater resources are insufficient to meet growing water demands, reclaimed water represents an alternate water supply (Alidina et al. 2015). MAR systems represent an attractive option for augmenting and improving groundwater quality as well as for environmental management purposes. These systems require minimal energy and chemical inputs for attenuation or removal of microbial and chemical compounds and do not create a waste stream, in contrast to processes like membrane treatment (Dillon 2005; Sudhakaran et al. 2013). It has been previously recognised that with training and demonstration projects MAR has potential to be a major contributor to the United Nations (UN) Millennium Goal for Water Supply especially for village supplies in semi-arid and arid areas (Dillon 2005).

Unresolved health concerns associated with drinking water drawn from polluted water sources certainly exist for wastewater reuse for potable purposes; however, a properly planned and managed water reuse project can produce higher quality finished water than unplanned reuse as is current common practice (Asano and Cotruvo 2004). Managed water reuse projects have historically provided multiple treatment barriers for the removal of microbial pathogens and organics to protect public health (Anders et al. 2004; Weiss et al. 2005; Hoppe-Jones et al. 2010; Betancourt et al. 2014). Collection data on human pathogenic virus concentrations and removal at wastewater treatment plants (WWTPs) is necessary to support a more accurate determination of log removal requirements for potable reuse projects. Equally important is the assessment of the relative transport and reduction of viruses during managed aquifer and recharge.

A National Research Council (NRC) Committee on Assessment of Water Reuse as an Approach for Meeting Future Water Supply Needs, convened by the Water Science and Technology Board, conducted a comprehensive study of the potential for water reclamation and reuse of municipal wastewater to expand and enhance the nation's available water supply alternatives (NRC 2012). The committee was tasked to address technical, economic, institutional, and social issues associated with increased adoption of water reuse and to provide an updated perspective of a wide range of reuse applications, including drinking water, non-potable urban uses, irrigation, industrial process water, groundwater recharge, and ecological enhancement. The committee performed a critical assessment of water reuse as an approach to meet future water supply needs, and showed that although reuse is not a panacea, the amount of wastewater discharged to the environment is of such quantity that it could play a significant role in the overall water resource picture and complement other strategies, such as water conservation. The committee recognised that de facto reuse of wastewater effluents as a water supply is common in many of the nation's water systems, with some drinking water treatment plants using waters from which a large fraction originated as wastewater effluent from upstream communities, especially under low-flow conditions. The committee also acknowledged that natural systems are employed in most potable water reuse systems to provide an environmental buffer. However, it cannot be demonstrated that such "natural" barriers provide any public health protection that is not also available by other engineering processes (e.g., advanced treatment processes, reservoir storage) (NRC 2012).

An environmental buffer is defined as a water body or aquifer that provides a "natural" separation of time and space between wastewater treatment and water supply. Environmental buffers act like natural treatment systems that may reduce the concentration of contaminants through various attenuation processes, provide an opportunity to blend or dilute the reclaimed water, and increase the amount of time between when the reclaimed water is produced and when it is introduced into the water supply. Environmental buffers may have different attributes that affect the removal of contaminants, the amount of dilution, or the residence time. Removal of viruses in riverbank filtration systems is a function of travel distance and time. The NRC committee acknowledges that without good data on site-specific characteristics, there will be considerable uncertainty about the ability of environmental buffers to remove contaminants. Constructed wetlands, soil-aquifer treatment, and riverbank filtration are all natural treatment processes that when combined with traditional and other advanced treatment processes may serve public perception (community acceptance to potable reuse projects) and treatment goals (AWWA/WEF 2008; NRC 2012).

This case covers key aspects of a case study that evaluated the removal of selected pathogenic human enteric viruses at three full-scale MAR systems located in different regions of the United States (Arizona, Colorado, and California). These MAR systems differ in treatment technologies and uses of application after recharge. The feasibility of MAR projects in the context of developing nations is also discussed.

2. Case Study: Virus Removal by MAR at Three Full Scale Operations

2.1. Description of the MAR Sites

The three different full-scale MAR sites studied represent different locations in the Western United States, different wastewater treatment processes prior to recharge, and different recharge operations and uses of application after MAR (Table 1).

The North Campus facility part of the Prairie Waters Project in Brighton, Colorado is situated along the South Platte River (Figure 1). Water is abstracted via a riverbank filtration well field located adjacent to the river. The site is located 18 miles downstream of the point of discharge of the largest wastewater treatment facility in the region. From the point of discharge, the wastewater takes approximately 18–20 h to reach the well field (during low flow conditions in the river). The wells are located at a distance of 100 to 300 feet (31 to 92 m) from the riverbank and are screened at depths of 30 to 50 feet (9 to 15 m) below ground surface. During the time of sampling, the river water was dominated by wastewater discharge (>85% based on flow data). Several abstraction

Table 1: MAR Systems and Treatment Technologies Prior to Recharge

MAR System/ Location	Wastewater treatment process prior to recharge	Recharge operation	Uses of application after recharge
North Campus facility part of the Prairie Waters Project in Brighton, (CO) along the South Plate River.	Activated sludge treatment (nitrification/denitrification) chlorination/ dechlorination	Riverbank filtration followed by infiltration via surface spreading basins (soil-aquifer treatment)	Aquifer recharge and recovery (indirect potable reuse)
Sweetwater Recharge Facility in Tucson (AZ) adjacent to the Roger Road wastewater treatment plant.	Biotowers (trickling filters) Chlorination/ dechlorination	Wastewater effluent fed to spreading basins	Groundwater recharge (winter) Landscape irrigation (summer)
Recharge basin testing facility located at the north end of San Gabriel River Coastal Basin Spreading Grounds in the Montebello Forebay (CA)	Activated sludge treatment (nitrification/denitrification) Secondary clarification tertiary dual-media filtration (anthracite and sand) chlorination/dechlorination	Infiltration via surface spreading	Aquifer recharge and recovery (indirect potable reuse)

wells of the North Campus facility along the river were sampled, some on several occasions. The water from all operational riverbank filtration wells was combined before being pumped to an adjacent aquifer recharge and recovery site where it was subsequently infiltrated via surface spreading basins for additional soil-aquifer treatment. Based on tracer tests (i.e., conductivity, temperature), the time for water from the

river to reach the wells was estimated to be between 5 and to greater than 15 days depending on well location. The soil composition at the site was characterised by alluvial sand with some gravel and silts.

Figure 1: Aerial map of the riverbank filtration well field along South Platte River at Brighton, Colorado showing locations of sampled wells (PW: production well) (Drewes et al. 2015)

The Sweetwater Recharge Facility is located in Tucson, Arizona adjacent to the Roger Road wastewater treatment plant (Figure 2). Wastewater effluent from the plant is fed to spreading basins for groundwater recharge, largely during the winter months. During the summer months, the water is subsequently extracted for use in landscape irrigation. Two monitoring wells were sampled during an infiltration event. The basins are underlain with a coarse sand and sandy gravel. The basins are infiltrated on wet-dry cycles varying from 2 to 7 days depending upon the season. Infiltration rates average about one meter per day.

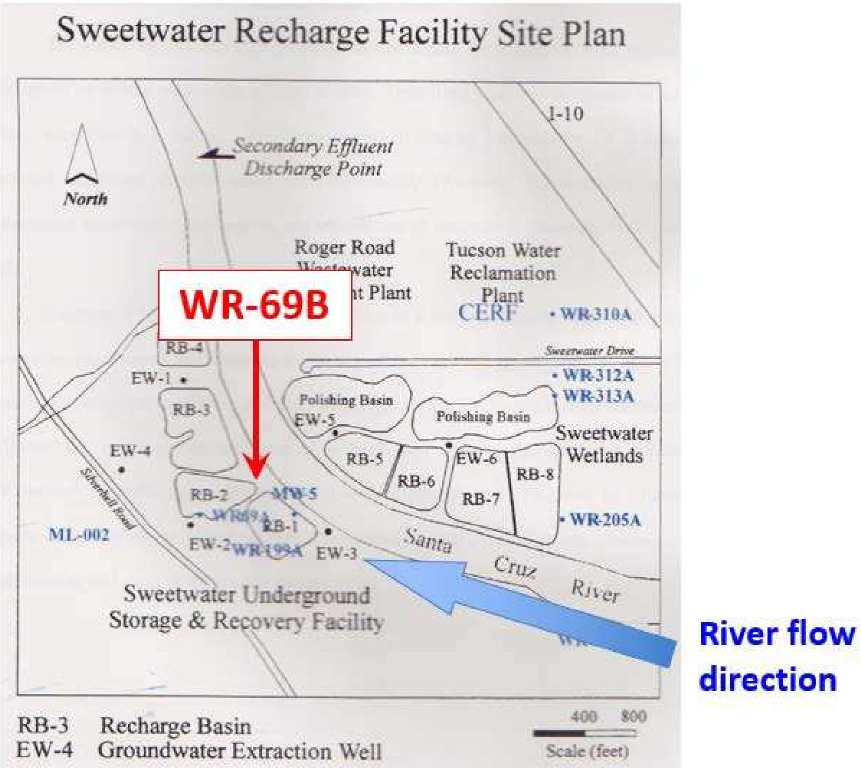

Figure 2: Sweetwater Recharge Facility in Tucson, AZ adjacent to the Roger Road Wastewater Treatment Plant (Drewes et al. 2015)

The San Gabriel River Coastal Basin Spreading Grounds in the Montebello Forebay, California, was constructed for the purpose of studying the fate of contaminants during MAR (Figure 3). The site receives wastewater effluents from the San Jose Creek Water Reclamation Facilities and the Whittier Narrows Water Reclamation Plant. The infiltration rate at the test basin during this study was determined to be in the range of 0.6 to 0.9 m per day.

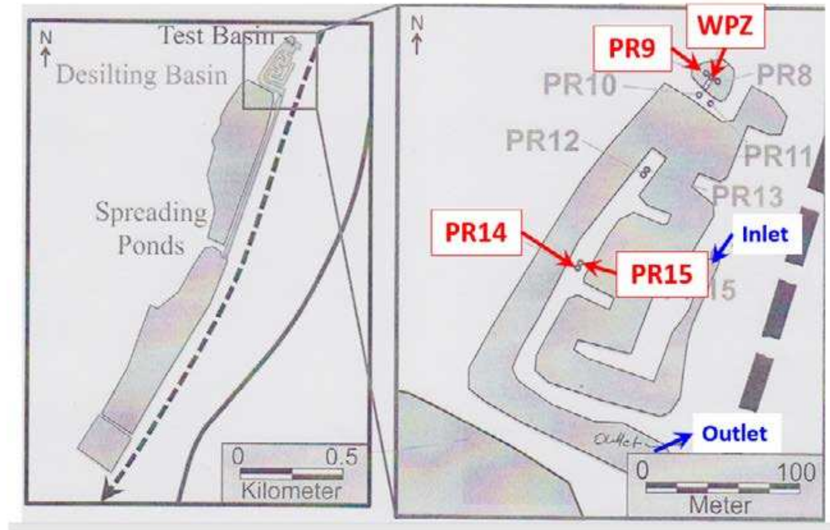

Figure 3: Recharge basin testing facility located at the North end of the San Gabriel River Coastal Basin Spreading Grounds in the Montebello Forebay, CA (Drewes et al. 2015)

2.2. Analysis of Viruses: Water Sample Collection and Virus Detection Methods

The enteric viruses selected for the study (Aichi virus and adenovirus) were those found in the greatest year round concentration in treated effluent (after activated sludge and trickling filter treatment) at two wastewater treatment plants in Tucson, Arizona. These viruses showed little and no seasonal variation in wastewater effluents. Data were also collected on the occurrence of pepper mild mottle virus (PMMoV), a plant virus that has been suggested as an indicator of wastewater contamination. Cultivable enteroviruses were included in the analysis because they have been previously studied the most at MAR operations and can easily be grown in cell culture. Reovirus was not part of the original testing plan. However, cell culture and molecular methods allowed the detection of this virus in one sample from the recharge site in Colorado. As a result, molecular tests were conducted to identify reovirus in all samples. Some technical details on sample collection, processing and analysis are given since the quality of the data is relevant for assessment of pathogens in MAR systems.

Sample volume sizes for pathogen analysis ranged from 2 L for wastewater effluent and river water and 5 to 400 L for the groundwater. Larger volume samples were processed on site by connection of a spigot at the wellhead to a filter housing and flow meter in series. Wastewater effluent, river water and groundwater samples up to 10 L membrane filtration with mixed cellulose esters membranes filters (HAWP, EMD Millipore Corporation, Billerica, MA, USA), as it has been previously used in numerous studies for the detection of viruses by qPCR in different water and wastewater matrices. For larger volumes of groundwater a virus concentration method using a NanoCeram filter (Argonide Corporation, Sanford, FL, USA) with a non-proteinaceous eluting solution (1.0% sodium polyphosphate solution with 0.05 M glycine) was used as they have been found to result in the concentration of fewer substances that interfere with virus detection by PCR. Viral DNA extraction for detection of adenovirus plus viral RNA extraction and Reverse Transcription for detection of enterovirus, Aichi virus and PMMoV were performed according to laboratory standard procedures. Real-time amplification was applied for detection of virus genomes performed with the LightCycler 480 Real-Time PCR Instrument II (Roche Applied Science, Indianapolis, IN, USA) using primers and probes described in detail elsewhere (Betancourt et al. 2014). Absolute quantification of the viruses studied was expressed as viral copy numbers or gene copies that were derived from standard curves. All groundwater samples that were positive for either enteric viruses or PMMoV were tested in cell culture for the presence of infectious viruses. Filter concentrates were assayed on the buffalo green monkey (BGM) kidney cell line. Rigorous attention to avoidance of laboratory contamination was maintained throughout the procedures following quality assurance and quality control guidelines implemented in the Laboratory of Molecular Biology and Cell Culture of the Department of Soil, Water and Environmental Science at the University of Arizona.

2.3. Virus Genomes and Removal by MAR Systems

The Colorado MAR site was sampled several times during the course of this study because of the large number of wells, continuous operation and ease of access. The river was dominated by upstream wastewater discharge (>85%) during the time the samples were

Table 2: Viruses in the Managed Aquifer Recharge System in Brighton, Colorado

Sample location	Date collected	Adeno-viruses (copies/L)	Entero-viruses (copies/L)	Aichi viruses (copies/L)	PMMoV (copies/L)	Travel time (days)
Discharge at Metro plant (Effluent)	10/09/12	3.22×10^5	5.42×10^3	1.23×10^4	8.99×10^6	-
	10/17/12	1.83×10^5	3.19×10^3	1.05×10^4	5.84×10^5	-
	10/30/12	1.07×10^5	5.27×10^4	4.73×10^4	3.41×10^6	-
South Platte River adjacent to well field	10/09/12	1.82×10^3	6.89×10^2	1.23×10^4	8.99×10^6	-
	10/17/12	9.56×10^4	3.35×10^1	1.05×10^4	5.84×10^5	-
	10/30/12	2.73×10^1	7.20×10^2	4.73×10^4	3.41×10^6	-
	05/29/13	8.59×10^2	2.52×10^2			
PW10	10/09/12	$<4.29^* \times 10^0$	**5.00×10^1**	$<8.57 \times 10^0$	**4.25×10^1**	~5
	10/17/12	$<4.29 \times 10^0$	$<8.57 \times 10^0$	$<8.57 \times 10^0$	**3.91×10^2**	~5
	10/30/12	$<4.29 \times 10^0$	$<8.57 \times 10^0$	$<8.57 \times 10^0$	**5.90×10^2**	~5
	05/29/13	$<6.00 \times 10^0$	$<1.20 \times 10^1$	$<1.20 \times 10^1$	**3.56×10^1**	~5
PW11	10/30/12	$<5.25 \times 10^0$	$<1.05 \times 10^1$	$<1.05 \times 10^1$	**8.55×10^2**	~5
PW 18	05/29/13	**1.20×10^0**	**4.00×10^{-1}**	**4.00×10^{-1}**	**1.35×10^1**	>10
PW20	1/10/13	$<1.50 \times 10^1$	$<3.00 \times 10^1$	$<3.00 \times 10^1$	**1.8×10^2**	>10
PW26	10/30/12	$<4.20 \times 10^0$	$<8.40 \times 10^0$	$<8.40 \times 10^0$	**4.04×10^3**	>15
	01/10/13	$<9.00 \times 10^0$	$<1.80 \times 10^1$	$<1.80 \times 10^1$	$<1.80 \times 10^1$	>15
Combined 500	01/10/13	$<1.20 \times 10^1$	$<2.40 \times 10^1$	$<2.40 \times 10^1$	$<2.40 \times 10^1$	5 to >15
Combined 1000	01/10/13	$<6.00 \times 10^0$	$<1.20 \times 10^1$	$<1.20 \times 10^1$	$<1.20 \times 10^1$	5 to >15
Combined 400	05/29/13	$<9.00 \times 10^{-1}$	$<1.80 \times 10^0$	$<1.80 \times 10^0$	**1.02×10^2**	5 to >15

PW – Production wells. PW10 located 100 feet from the riverbank. All other sampled wells were on average 300 feet from the riverbank. Combined 400, 500, and 1000 - Indicates volume of water sampled in litres from combined collector.

ND – not done. PMMV - Pepper mild mottle virus collected. Adenoviruses and PMMoV were observed in the highest concentration in the wastewater effluent that has been sampled at the treatment plant prior to discharge into the South Platte River (Table 2). During travel down the river the concentration of viruses in the wastewater decreased by 90 to 99% (1 to 2 log10) on average as detected by qPCR. PMMoV was detected in all of the abstraction wells adjacent to the river and in the combined riverbank filtered water (the water from the producing wells is mixed), which is subsequently conveyed to surface spreading basins for infiltration at the aquifer recharge recovery facility of the North Campus. Enteroviruses were detected in one of the wells (PW-10) on one occasion by qPCR. This sample was also positive for infectious virus using cell culture and reovirus was identified by PCR. No amplification was observed for adenoviruses, enteroviruses and Aichi viruses confirming that these pathogenic viruses were not present in the sample.

At the California site, only adenoviruses were detected by qPCR at a low number in the treated effluent (Table 3). The wastewater at this site receives the greatest amount of treatment prior to recharge as compared to the sites in Colorado and Arizona and this may explain the low numbers of virus in the samples collected. However, it could also be related to other factors such as incidence of infection in the community and seasonal differences. Only PMMoV was detected in the samples from shallow groundwater at the site. It was only detected in groundwater of wells with three or fewer days of travel time in the subsurface.

At the Sweetwater Recharge site all the studied viruses were detected in the wastewater effluent in large concentrations. Both Aichi viruses and PMMoV were detected in one well with a 5-day travel time. None of the viruses were detected in a well with a 14-day travel time. Unlike the other two sites, attempts were made to sample the same effluent as it travelled from the basins to the monitoring well. The sampling was timed (synoptic sampling) so that the same body of water was sampled as it travelled through the subsurface. Samples showing the presence of any virus were assayed in cell culture and no infectious virus was detected in any of the samples from California or Arizona.

The relative amount of removal of the different viruses was calculated for the different sites when viruses were detected in the wastewater effluent being recharged. Table 4 summarises the degree of estimated removal of the different viruses at the study sites in wells with different travel times.

Table 3: Viruses in Managed Aquifer Recharge Systems in California and Arizona

Sample Location	Adenoviruses (copies/L)	Enteroviruses (copies/L)	Aichi viruses (copies/L)	Pepper mild mottle virus (copies/L)	Travel time (days)
Test Basin, Montebello Forebay, California					
Effluent	**8.07×10^{1}**	$<6.60 \times 10^{1}$	$<6.60 \times 10^{1}$	$<6.60 \times 10^{1}$	-
Well WP-Z	$<6.50 \times 10^{0}$	$<1.30 \times 10^{1}$	$<1.30 \times 10^{1}$	**7.59×10^{2}**	0.45
Well PR-9	$<6.90 \times 10^{0}$	$<1.38 \times 10^{1}$	$<1.38 \times 10^{1}$	**2.10×10^{1}**	3.5
Well PR-15	$<6.30 \times 10^{0}$	$<1.26 \times 10^{1}$	$<1.26 \times 10^{1}$	$<1.26 \times 10^{1}$	44.5
Well PR-14	$<7.20 \times 10^{0}$	$<1.44 \times 10^{1}$	$<1.44 \times 10^{1}$	$<1.44 \times 10^{1}$	128.5
Sweetwater Recharge Site, Arizona					
Effluent	**9.37×10^{3}**	**3.46×10^{4}**	**4.76×10^{4}**	**5.15×10^{6}**	-
Well MW5	$<8.40 \times 10^{1}$	$<1.68 \times 10^{2}$	**1.52×10^{4}**	**1.44×10^{6}**	5
Well WR-69B	$<3.56 \times 10^{0}$	$<7.11 \times 10^{0}$	$<7.11 \times 10^{0}$	$<7.11 \times 10^{0}$	~14

Determination of the degree of removal was limited by the concentration of the viruses in the treated wastewater being applied to the sites and the volume of concentrate assayed. It was usually easier to determine removal of PMMoV because it was usually present in the largest numbers in the wastewater effluent. Aichi and PMMoV were removed to a similar degree after a 5-day travel time at the Sweetwater Recharge site. However, the removal of Aichi viruses exceeded 2.8 logs after 14 days travel time and PMMoV was removed by almost 5 logs. Only the removal of adenoviruses could be determined at the test basin site in California as it was the only virus detected in the applied wastewater effluent. It was reduced by at least one log in less than a day of travel time. It was interesting that removal of the PMMoV at the Colorado site was almost identical for the three wells tested, suggesting a removal efficiency in the 3 to 4 log range. At all of the sites, PMMoV appeared to be removed the least and should be considered as a conservative tracer of the enteric viruses studied.

The only infectious virus detected in this study was reovirus, a double-stranded (ds) RNA virus included within the family Reoviridae. Because it has been difficult to associate reoviruses with specific illnesses in humans they have not received as much study as the other enteric viruses. Several studies using cell culture infectivity have found them to occur in concentrations greater than enteroviruses in untreated wastewater and after disinfection by chlorination. They are more resistant to UV light disinfection than the enteroviruses. They also appear to survive for prolonged periods of time in water. In a study of drinking water wells, it was the most common virus detected by PCR. Thus, it would appear that reoviruses may warrant additional studies to assess their removal by MAR.

The results of the study indicated that residence time played an important role in the removal efficiency of pathogens (i.e., viral attenuation) by the three natural treatment systems. All viruses were removed below detection limits of the method during riverbank filtration and soil-aquifer treatment. The ability to quantify the removal of human enteric viruses was limited by the concentrations of the particular virus in the infiltrated wastewater, but it appeared that at least a ~2 log removal or more could be expected with a travel time of ~15 days. The study also revealed that PMMoV might serve as a conservative tracer of virus removal for managed aquifer recharge operations. The occurrence of reoviruses in a riverbank filtration well warrants further study. Reoviruses are ubiquitous

Table 4: Log Removals of Viruses by Recharge at the Three Managed Aquifer Recharge Systems

Site/well	Well depth (feet)	Residence time (days)	Adenovirus	Enterovirus	Aichi virus	PMMoV
Arizona						
MW5	30	5	>2.05	>2.31	**0.50**	**0.55**
WR-69-B	152.2	~14	>3.42	>3.69	>3.83	>5.86
California						
WP-2	21.2	0.45	>1.09	ND	ND	ND
PR-9	35	3	>1.07	ND	ND	ND
PR- 15	40.5	49.5	>1.05	ND	ND	ND
PR-14	70.5	128.5	>1.11	ND	ND	ND
Colorado						
PW10*						
#1 (10/09/12)	30	~5	>2.63	**1.15**	>2.61	**3.76**
#2 (10/17/12)			>4.35	ND	>3.07	**2.72**
#3 (10/30/12)			>0.80	>2.70	>3.35	**2.76**
#4 (05/29/13)			>2.16	ND	>3.31	**3.69**
PW11	29	~5	>0.72	>1.84	>2.49	**2.60**
PW26	24	>15	>0.81	>1.93	>2.58	**1.92**

PW10 was sampled four different times
ND = not detected in treated wastewater
NT = treated wastewater not yet tested

in their geographical distribution and therefore have been reported to occur in groundwater from different geographical areas. These viruses are also very stable in the environment. The application of next generation sequencing technologies (e.g., metagenomics) for a complete representation of the viruses present in environmental waters may expand our knowledge about virus diversity, fate, and distribution in managed aquifer recharged systems.

3. MAR Projects in the Context of Developing Countries

MAR systems have been recognised as simple, low-tech, and cost-effective treatment systems that may be economically viable for developing countries (Maliva 2014). However, there are many environmental and public health concerns related to sewage contamination in these countries, e.g. lack of wastewater collection and treatment and/or inadequate treatment of wastewater. Moreover, good-quality water in high demand in urban and overpopulated peri-urban areas in developing countries exerts significant pressure on scarce and highly impacted water resources. In this context, water reuse makes a lot of sense for these regions, however any water reuse project may not be feasible until wastewater collection and treatment can be adequately addressed. MAR systems also require sustainable management to successfully maintain the attributes necessary for potable and non-potable water reuse.

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References

Alidina, Mazahirali, Dong Li, Mohamed Ouf, and Jörg E. Drewes. 2014. "Role of primary substrate composition and concentration on attenuation of trace organic chemicals in managed aquifer recharge systems." *Journal of Environmental Management* 144:58–66. doi:10.1016/j.jenvman.2014.04.032.

Anders, Robert, William A. Yanko, Roy A. Schroeder, and James L. Jackson. 2004. *Virus fate and transport during recharge using recycled water at a research field site in the Montebello Forebay, Los Angeles County, California, 1997–2000; Scientific Investigations Report 2004-5161*. U.S. Geological Survey: Reston, Virginia.

Asano, Takashi, Franklin Burton, Harold L. Leverenz, Ryujiro Tsuchihashi, and George Tchobanoglous. 2007. *Water Reuse: Issues, Technologies, and Applications*. New York: McGraw-Hill.

Asano, Takashi, and Joseph A Cotruvo. 2004. "Groundwater recharge with reclaimed municipal wastewater: Health and regulatory considerations." *Water Research* 38:1941–1951.

AWWA/WEF (American Water Works Association and Water Federation). 2008. *Using reclaimed Water to Augment Potable Water resources*. 2nd Ed. Denver, CO: American Water Works Association.

Bekele, Elise, Simon Toze, Bradley Patterson, and Simon Higginson. 2011. "Managed aquifer recharge of treated wastewater: Water quality changes resulting from infiltration through the vadose zone." *Water Research* 45:5764–5772. doi:10.1016/j.watres.2011.08.058.

Betancourt, Walter Q, Masaaki Kitajima, Alexandre D. Wing, Julia Regnery, Jörg E. Drewes, Ian L. Pepper, and Charles P. Gerba. 2014. "Assessment of virus removal by managed aquifer recharge at three full-scale operations." *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering* 49:1685–1692. doi: 10.1080/10934529.2014.951233.

Clinton, Tracy. 2007. Reclaimed Water Aquifer Storage and Recovery: Potential Changes in Water Quality. WateReuse Foundation Report. Alexandria, VA, USA: WateReuse Foundation.

Dillon, Peter, Paul Pavelic, Declan Page, Helen Beringen, and John Ward. 2009. Managed aquifer recharge: An Introduction. Waterlines Report Series No. 13, February 2009. Canberra: Commonwealth of Australia. http://www.nwc.gov.au/__data/assets/pdf_file/0011/10442/Waterlines_MAR_completeREPLACE.pdf.

Dillon, Peter. 2005. "Future management of aquifer recharge". *Hydrogeology Journal* 13:313–316.

Drewes J., Regnery J., Dickenson E., Gerba C.P., Snyder S.A., Missimer T. 2015. Role of Retention Time in the Environmental Buffer of Indirect Potable Reuse Projects: An

Investigation of Managed Aquifer. WateReuse Foundation Report. Alexandria, VA, USA: WateReuse Foundation.

Hoppe-Jones, Christiane, Gretchen Oldham, and Jörg E. Drewes. 2010. "Attenuation of total organic carbon and unregulated trace organic chemicals in U.S. riverbank filtration systems." *Water Research* 44:4643– 4659. doi:10.1016/j.watres.2010.06.022.

Maliva, Robert G. 2014. "Economics of managed aquifer and recharge." *Water* 6:1257–1279.

Missimer Thomas M., Jörg E. Drewes, Robert G. Maliva, and Gary Amy. 2011. "Aquifer Recharge and Recovery: Groundwater Recharge Systems for Treatment, Storage, and Water Reclamation." *Ground Water* 49:771.

National Research Council. 2012. *Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater*. Washington, D.C.

Pang, Liping. 2009. "Microbial removal rates in subsurface media estimated from published studies of field experiments and large soil cores." *Journal of Environmental Quality* 38:1531–1559. doi:10.2134/jeq2008.0379.

Sharma Saroj K., and Gary Amy. 2011. "Natural Treatment Systems." In *Water Quality and Treatment: A Handbook on Drinking Water*, edited by James K. Edzwald, 1–33. Denver, Colorado: American Water Works Association.

Sudhakaran, Sairam, Sabine Lattemann, and Gary L. Amy. 2013. "Appropriate drinking water treatment processes for organic micropollutants removal based on experimental and model studies – A multi-criteria analysis study." *Science of The Total Environment* 442:478–488. doi:10.1016/j.scitotenv.2012.09.076.

Weiss W. Joshua, Edward J. Bouwer, Ramon Aboytes, Mark W. LeChevallier, Charles R. O'Melia, Binh T. Le, and Kellogg J. Schwab. 2005. "Riverbank filtration for control of microorganisms: results from field monitoring." *Water Research* 39:1990–2001. doi:10.1016/j.watres.2005.03.018.

CASE 2

Water Sensitive Urban Design for Metropolitan Lima, Peru – "Wastewater Treatment Park: The Children's Park" – Application of Vertical Flow Constructed Wetlands in Public Open Space for Reuse of Treated Wastewater (Peru)

Rosa Miglio, Alexandra Garcia, Eva Nemcova, and Rossana Poblet[1]

Abstract

The Peruvian capital, Metropolitan Lima, with over 9 million inhabitants located in the desert of the Pacific coast is characterised by inequalities in access to basic services such as drinking water and wastewater treatment as well as access to healthy green areas. Lima is one of the Latin American cities with the amount of least green areas per inhabitant (Economist Intelligence Unit 2010). Many public and private green areas in Lima are irrigated either with scarce potable water or with polluted surface water, while the reuse of wastewater remained as low as 10% in 2011 (Kosow et al. 2013). Within the research project LiWa (Lima Water) the Lima Ecological Infrastructure Strategy (LEIS) was developed. Its aim is to integrate landscape and urban planning and design with water management in order to support the urban water cycle – including the reuse of wastewater – and to increase access to green public spaces that perform ecosystem services for the benefit of the communities. At a technical level the use of constructed wetlands appears to be one possible water-sensitive urban design strategy for a dry region such as Lima. They generate green areas by themselves and

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therefore have a high potential to be integrated in open space design. In 2013 the "Wastewater Treatment Park – Children's Park", located in the San Martin de Porres district, was built as a recreational area with a vertical constructed wetland treating water from a polluted irrigation channel. The wastewater treatment plant was designed by Akut Peru, and included pre-treatment with bars and settler, and a vertical flow constructed wetland; the plant treats 5.57 m^3 d-1 in an area of 50 m^2 resulting in a hydraulic loading of about 0.11 m^3 m^{-2} d^{-1}. The polluted water has a variable BOD5 and turbidity with peaks of 15.4 mg/L and 1000 NTU respectively. Faecal coliforms vary over a wide range from $3x10^2$ to 10^4 CFU/100 ml; and parasites (Ascaris toxocara) were present. The National Agrarian University La Molina (UNALM)-Lima conducted monitoring of water quality and social acceptance; the water quality monitoring shows that the water quality after the treatment process is significantly improved, reducing health risks to users of the park and reducing negative environmental aspects such as smell and the presence of vectors of waterborne diseases. This case describes the project, presents the monitoring results, discusses the constraints and challenges of such a concept, and shares the participative approach taken to co-design a water sensitive urban design project which can create socio-environmental awareness to overcome negative conditions over contested peri-urban areas.

Keywords: Lima, arid regions, constructed wetland, ecological infrastructure, green-open space, reuse of wastewater, urban water cycle, wastewater treatment, water-sensitive urban design

1. Introduction

Metropolitan Lima suffers from a water shortage for different reasons: low annual precipitation (< 15 mm), seasonal rivers with water stress (0-10 m^3 sec^{-1} from May to December), polluted waters (Fernández-Maldonado 2008), and unsustainable and inefficient water management. The fast population growth in previous decades, the lack of implementation and modernisation of urban and regional planning instruments, the economic crisis, and other factors have led to a vast expansion of informal settlements, especially in peri-urban areas. Many of these settlements and almost 1 million people do not have access

to the public water supply or wastewater services. They occupy land such as river corridors or agricultural valleys where they are exposed to risky living conditions and at the same the loss of these areas means the loss of areas providing essential ecosystem services to the city. In many peri-urban areas there is less than 2 m^2 of green areas per person while other richer areas have more than 20 m^2 of green areas per person (Eisenberg et al. 2014, 26), manifesting the great inequality in distribution throughout the city. Also the richer districts can afford to use potable water for the irrigation of green areas, while in poorer and mostly peri-urban zones raw or poorly treated wastewater is used for irrigation posing health hazards for the population. The available water resources are not efficiently used, with wastewater reuse levels as low as only 10% in 2011. The climate change effects over the Andean mountains that are predicted to lead to decreasing water supplies (Kosow et al. 2013) will increase the challenges Lima is facing. Among the main obstacles for integrated planning is the lack of a unified view of the city shared by urban and open space planners and designers and water engineers. Therefore, to reduce unsustainable practices and urban development processes, an urban water paradigm shift towards more sustainable practices that take into account the urban water cycle are needed (Eisenberg et al. 2014).

As the background of Lima requires urgent solutions, the Institute of Landscape Planning and Ecology (ILPOE) at the University of Stuttgart (Germany), as part of the research project "Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change - Concepts for Metropolitan Lima, Peru, Lima Water - LiWa", developed the "Lima Ecological Infrastructures Strategy" (LEIS). The strategy consists of (1) LEIS Principles to support strategic urban planning and policy making leading to water-sensitive urban development, (2) LEIS Tool to support urban planning to consider the relationship between water and green open spaces, and (3) LEIS Manual with water-sensitive urban design guidelines for project development. Attending the technical support request by the San Martin de Porres municipality, the LiWa project had chosen the Lower Chillon River watershed to demonstrate the application of LEIS on different scales. The focus of this case is the implemented pilot project "Wastewater Treatment Park - Children's Park" that serves as a Water-Sensitive Urban Design (WSUD) example. The implementation process of the pilot project, its design parameters and the results of water quality monitoring, social acceptance and lessons learned will be described and discussed. It aims to provide knowledge for the future application of constructed wetland technology in public open spaces in Metropolitan Lima. In a broader scope it aims to reflect on the potentials of LEIS and WSUD as integrative planning and design strategies that support cities in dry climatic conditions to prepare and cope with water scarcity and climate change effects.

2. Aim and Objectives of the Project

The main aim of the pilot project was to implement an example of a WSUD park that treats contaminated water for reuse in the irrigation of green areas, uses less water than a conventional park in Lima, and at the same time is an attractive public space for the community. Other objectives included:

- To promote the use of treated wastewater for reuse in green areas.
- To create new healthy green areas reducing desertification and dust in the area and also benefiting the local community.
- To demonstrate opportunities to improve wastewater quality through ecological technologies such as constructed wetlands and integrate these components into public spaces.
- To raise awareness and show the importance of irrigation channels as a permanent source of water to support green area generation and agricultural activities.
- To create awareness of the desert environment and its limited water resources in relationship to the water demand of green areas by using only native plant species with low water consumption in the park design.
- To create synergies among key players, mainly rural and new urban residents, who use and benefit from the waters transported by the irrigation channels.
- To serve as a demonstration project for wastewater reuse.

3. Context

The study area is over former agricultural land called Chuquitanta, in the lower Chillon River watershed in Lima North, in the San Martin de Porres district (Figure 1). Chuquitanta is crossed by a network of channels (called '*acequias*') which are part of an ancient irrigation system. Land use here has been changing in recent decades due to rapid urban growth and urban speculation. The area has been rapidly transformed by private developers implementing informal housing programmes. Due to the lack of municipal recognition, the new residences lack basic services and infrastructure, and therefore discharge their wastewater and solid waste into irrigation channels which irrigate not only agricultural land but also green recreational areas. The poor water quality poses a health threat to consumers of local crops as well as users of the green areas. Moreover, due to the urban regularisation processes the *acequias* are being converted into concrete irrigation channels which prevent water from infiltrating the soil and replenishing groundwater. Several channels have been closed completely which led to desertification of once green parks and has in result triggered social conflicts. In this context, a new approach to water and open space design is needed to reinstate local irrigation channels as sustainable sources of water.

Figure 1: Lower Chillon River Watershed, Metropolitan Lima (Photo: Evelyn Merino Reyna)

4. Project Description

4.1. Location

The project is located in La Florida II, one of the new informal housing programmes developed on former agricultural land, and is owned by the real estate company Residential SAC. At the fringe of La Florida II, within its administrative boundary, passes the irrigation channel San José on its way to agricultural land. The settlement is in the process of obtaining urban legal rights which will be received once the real estate company completes all the basic infrastructure. Currently water has to be supplied 2 to 4 times per week by water trucks selling approximately 200 litres (water cylinder capacity) per 2 PEN (0.5 US$ each cylinder) at a price approximately 10 times higher than formal areas connected to public network. The quality of this delivered water is not good, and many residents buy bottled water for human consumption.

Figure 2: La Florida II settlement: San José irrigation channel and the project area on the left of the channel before construction (Photo: Eva Nemcova)

La Florida II comprises around 600 inhabitants and covers approx. 31,740 m^2. It includes 8 blocks over 141 single plots, one area reserved for education and two parks: Park 1 (1,992.2 m^2) and Park 2 (598.16 m^2). The larger park (Park 1) is used mainly by male adults for football practices and is irrigated with polluted water from the channel delivered by a pipe. The pilot project is located in the smaller park (Park 2) situated directly next to the irrigation channel (see Figure 2). In 2012 this natural canal was converted into a concrete channel to comply with the requirements for obtaining the formalisation of La Florida II. The construction led to the removal of trees and grass previously maintained by neighbours. The destruction of the plants triggered much local communal strife and generated further social and legal conflicts. Likewise conflicts arose between the community association and the Chuquitanta irrigation committee for modifying the acequia route and concreting its borders, as well as the municipal authorities, for requesting this work as part of an urban regularisation process that acts "against the environment".

4.2. Key Actors

The main actors involved with the project are the community from La Florida II and the community representatives, the Chuquitanta Irrigation Commission, the Management of Public Utilities and the Environment of the Municipality of San Martin de Porres, and the ILPOE's implementation team.

During the project development different reasons led to the key actors' involvement and participation, including long-term conflicts and social, environmental, political and administrative disputes. The park site is located in an area that was formerly an "ecological park" and that was destroyed to fulfil municipal recognition as an urban area or *habilitación urbana*. Under these conditions the community requested technical support to build a new park. Therefore, the park development, following a participative approach, was used to re-establish dialogue among neighbours, the Chuquitanta Irrigation Commission, and the local authorities. During the process it was perceived that the park development helped to improve relationships between the different actors. But tensions arose around the issue of maintaining the park. Nevertheless, it is important to mention that the partnership between these stakeholders is critical for the current and future sustainability of the park and its treatment system.

4.3. Project Methodology

The process was developed to consider the following stages:

- **Initial assessment** included the study of socio-economic and environmental conditions, identification of key players, land survey and water quality test.
- **Community training and participatory design workshops** included design workshops with the community to define the concept, functions and programme. And served to raise environmental awareness in general.
- **Constructed wetland and design integration** included the design and elaboration of construction documents for treatment system and park components.
- **Implementation** of the park. Public electrification to support the constructed wetland performance and public lighting inside the park was obtained in addition to the permission from the Chuquitanta Irrigation Commission to use water from the San José channel.
- **Testing and training** included the testing of the treatment system, training of the municipal officers in operating and maintaining the constructed wetland and the park in general.
- **Initial park monitoring and performance**: the water monitoring started after the inauguration of the park and was conducted by a UNALM student as a final project. In addition, regular visits led by former ILPOE project manager Rossana Poblet to speak with main actors and follow up on the park performance and maintenance by municipal authorities and neighbours were carried out.

4.4. Main Project Characteristics

The park comprises three main parts including (1) the constructed wetland system with a reservoir of treated wastewater, (2) a green recreational area with fruit trees for passive recreation, and (3) a play area with dry surfaces and trees to provide shade. Figure 3 shows the proposal and the park at its inauguration in August 2014.

Figure 3: Wastewater Treatment Park – Children's Park on the inauguration day in August 2014, consisting of: 1) treatment system with constructed wetland and reservoir, 2) green recreational area with fruit trees, and 3) play area with dry surfaces (Photo: Evelyn Merino Reyna)

4.4.1. Park Water Demand

Only 40% of the total park area is planted with grass and native fruit trees. The remaining area consists of dry surfaces with solitary trees of native species (mimosa) and xerophytes. The careful selection of vegetation and the use of pressurised irrigation systems resulted in a low overall water demand (~1 $m^3 d^{-1}$) for the total area. Thus, the remaining treated water can help to irrigate the second park (~2000 m^2) in La Florida II.

4.4.2. Description of the Wastewater Treatment System

The wastewater treatment plant was designed by Akut Peru and included a pre-treatment system with bars (20 mm distance) and a settler, a vertical flow constructed wetland model WTL-Rotaria, and a reservoir. The wetland has an area of 50 m^2 (5 m x 10 m) and a total depth of 0.90 m. It was designed as an elevated flower bed to utilise the slope in the par k, with 0.40 m underground and 0.5 m above ground.

The constructed wetland was filled with coarse sand and gravel according to the details described in Table 1, from the bottom to the top of the constructed wetland.

Table 1: Constructed Wetland Filling Material Distribution

Gravel to cover the drainage pipe	**0.15**
Coarse sand without dust	**0.50**
Gravel Surface protection	**0.10**
Freeboard	**0.15**
Total height	**0.90**

Source: Akut Peru

Initially two different vegetation species were planted, Vetiver *Chrysopogon zizanioides*, and *Paraguitas Cyperus alternifolius*, but most of the Paraguitas plants did not establish well and three months after the first plantation they were replaced with Vetiver. A few Paraguitas plants did remain in the bed and are still present in the wetland.

The treatment system is an automatized system that depends on pumping, which feeds the treatment plant in cycles of 48 hours, making a total of 3 cycles per week. The feeding of the vertical wetland is programmed according to pulses, which ensures the oxygenation of the system.

The plant treats 5.57 m^3 d^{-1} distributed in an area of 50 m^2 resulting in a hydraulic loading of about 0.11 m^3 m^{-2} d^{-1}. The polluted water has a variable BOD5 and turbidity with peaks of 15.4 mg/L and 1000 NTU respectively. Faecal coliforms vary over a wide range from $3x10^2$ to 10^4 CFU/100 ml; and parasites (Áscaris toxocara) were present. However, only one analysis of faecal coliforms was performed and is presented here as a preliminary result.

4.4.3. Design of Open Space and Integration with Treatment Technology

The constructed wetland is situated at the highest point of the park in order to reduce the need for pumping. The elevated edge of the constructed wetland was designed as a seating bench with a wooden deck and educational panels informing the community about the water source and quality, treatment process and reuse. The plant species of the constructed wetland contribute significantly to the aesthetic aspect of the treatment system and are key features of the park. Figures 4 and 5 show some images of the Wastewater Treatment Park – Children's Park a year after inauguration.

Figure 4: Constructed wetland with the seating bench, wood deck and educational panel about the San José water source, "San Pepito droplet" (Photo: Alexandra Garcia)

Figure 5: Green productive recreational area and the dry play area in the foreground (Photo: Alexandra Garcia)

5. Water Quality Monitoring and Results

Physicochemical and microbiological parameters were analysed weekly for two months, seven samples were tested using APHA-AWWA-WEF Standard methods.

Temperature and pH were measured in the field; the other parameters including the microbiological parameters were measured in the Sanitation and Environment Lab of UNALM. The results of the physicochemical and microbiological analysis obtained to date are showed in Table 2. Preliminary results for parasites are showed in Table 3.

5.1. Removal Efficiency

The analysis of the monitoring water quality showed the following results:

- The pH of the wastewater was slightly alkaline. It entered the treatment system with an average value of 7.66 and at the outlet a slight reduction is registered with an average value of 7.39. This could be linked to the microbial activity that acidified the environment (carbonic acid), but this value does not affect the use of treated water for the irrigation of green areas.
- Regarding electric conductivity, the influent of the system had an average value of 548 µS/cm and in every sample it increased reaching a value of 922 µS/cm on average. However, this increase does not influence the use of treated wastewater for the irrigation of green areas according FAO guidelines.
- Turbidity was reduced drastically in the settler and wetland outlet (96%), the average value in the outlet of the wetland being 1.66 NTU.
- BOD5 reduction in the system reached an average value of 77%, but for the last two samples (1 year and 4 months after the treatment plant started operations) efficiency increased to 93 % on average.
- Faecal coliform reduction in the system reached an average of 80%, although in most cases at the outlet of the system the value of faecal coliform did not reach 1,000 CFU/100 ml.
- Regarding parasites, it was possible to perform only one test. In this sample of the raw wastewater 15 eggs/L were found and 100% were removed at the outlet of the wetland. The species identified was *Ascaris taxocara*, which is associated with pollution originating from the excreta of domestic animals such as dogs and cats.
- Water turbidity samples from the three sampling points are shown in Figure 6: inlet of the system (EI), outlet to the settler (ES) and vertical wetland outlet (EH), respectively.

Figure 6: Observed turbidity in water sampling from inlet of the system (EI), outlet to the settler (ES) and vertical wetland outlet (EH) (Source: Alexandra Garcia)

Table 2: Preliminary Water Test Results Including Physicochemical and Microbiological Analysis

Nº	SAMPLING POINT	PRELIMINARY REPORTS						
		Temper. (°C)	pH Standard	Electric. Conduct. (CE) (µS/cm)	Turbidity (NTU)	Suspended solids (mg/l)	BOD5 (mg/l)	FAECAL COLIF (CFU/ 100 ml)
1	EI	N	7.35	1044	23	2000	15.37	N
	ES	N	7.14	1184	19.4	1800	13.96	-
	EH	N	7.15	1271	1.1	200	3.9	N
2	EI	27.2	7.73	1044	162	600	14.2	300
	ES	27.5	7.67	1184	140	200	9.2	-
	EH	28.6	7.58	1271	1.84	<100	4.67	< 20
3	EI	30.0	7.93	544	212	2000	9.53	4540
	ES	29.6	7.53	516	44.2	200	2.94	-
	EH	29.9	7.54	625	1.98	<100	1.35	680
4	EI	26.9	7.71	346	94	1000	2.68	420
	ES	27.2	7.50	477	47.5	200	1.27	-
	EH	27.6	7.55	592	0.75	<100	0.56	240
5	EI	23.8	7.58	502	83.1	500	6.17	980
	ES	23.6	7.71	501	73.1	100	3.17	-
	EH	23.3	7.64	612	4.07	<100	2.87	110
6	EI	N	7.71	368	>1000	15600	7.75	>10000
	ES	N	7.55	510	953	3000	3.22	…
	EH	N	7.20	1395	1.25	<100	0.45	1520
7	EI	N	7.63	599	102	5200	9.06	7740
	ES	N	7.46	506	30.4	600	2.94	…
	EH	N	7.10	1282	0.64	<100	0.71	1080

Table 3: Preliminary results, Wastewater Treatment Park – Children's park – parasites

Nº	SAMPLING POINT	PRELIMINARY REPORTS	
		Eggs number/L	SPECIES FOUND
1	EI	15	*Ascaris Toxocara*
	EH	0	*Ascaris*

EI: inlet point to the wastewater treatment system, ES: outlet of settler, EH: outlet of wetland, N: undetermined

6. Social Perception – Level of Acceptance

A survey was conducted in order to evaluate the sustainability of the treatment system and its acceptance by the local inhabitants. In total 20 local inhabitants were part of the survey, most of them were women younger than 35 years old and were living for less than 5 years in the area (Figure 7).

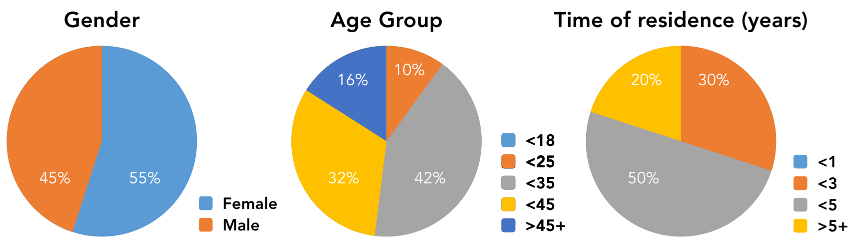
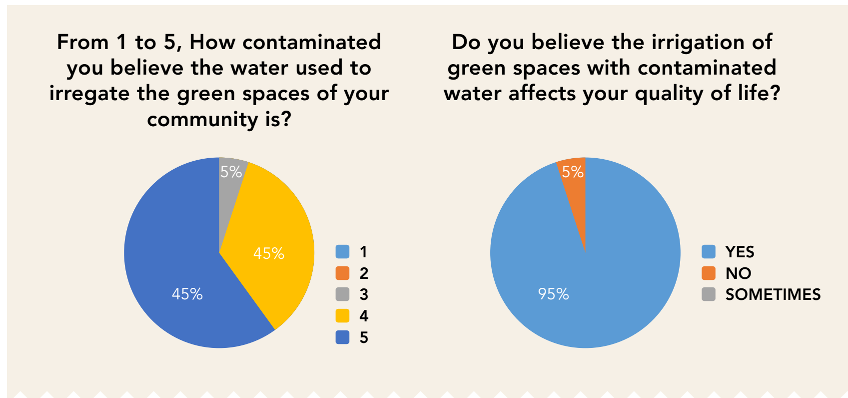


Figure 7. Profile of respondents to the survey to assess the treatment system (Source: Garcia Rospigliosi 2015)

The survey questions were related to how aware inhabitants are about health risks connected to the use of polluted water from the channel for irrigating green areas, how it is affecting their lives, and to what extent they would be willing to participate in combatting the contamination. A scale from 1 to 5 was used to set the degree of contamination from 1 = "it is not polluted" through 5 = "it is highly polluted". The results are shown in Figure 8.



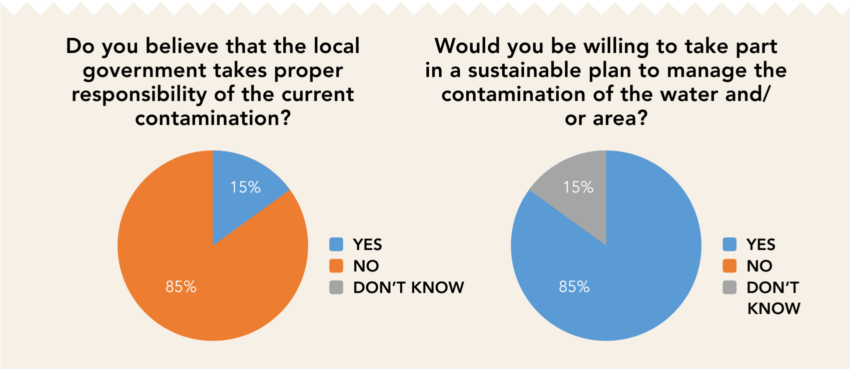
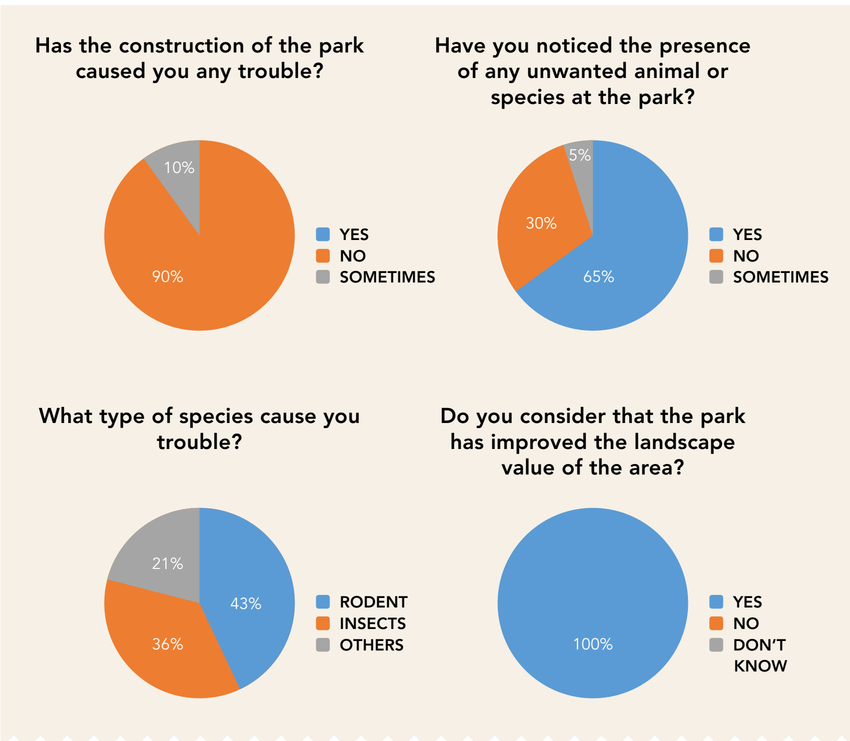


Figure 8: Perception of the pollution level of water in the irrigation channel and willingness to participate in a sustainable plan to management it (Source: Garcia Rospigliosi, 2015)

The inhabitants were asked how they perceive the park, their complaints regarding the park, how they perceive the management of the park, and if they would be willing to get involved in the management. The results are shown in Figure 9.



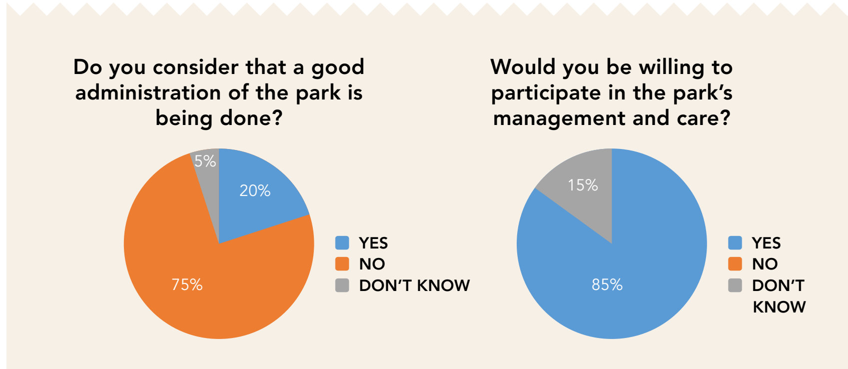


Figure 9: Perception regarding the park construction, complaints made, management and willingness to participate in a management programme (Source: Garcia Rospigliosi, 2015)

Finally, the survey focused on determining how much knowledge the inhabitants have gained about the treatment system installed in the park. The results are shown in Figure 10.

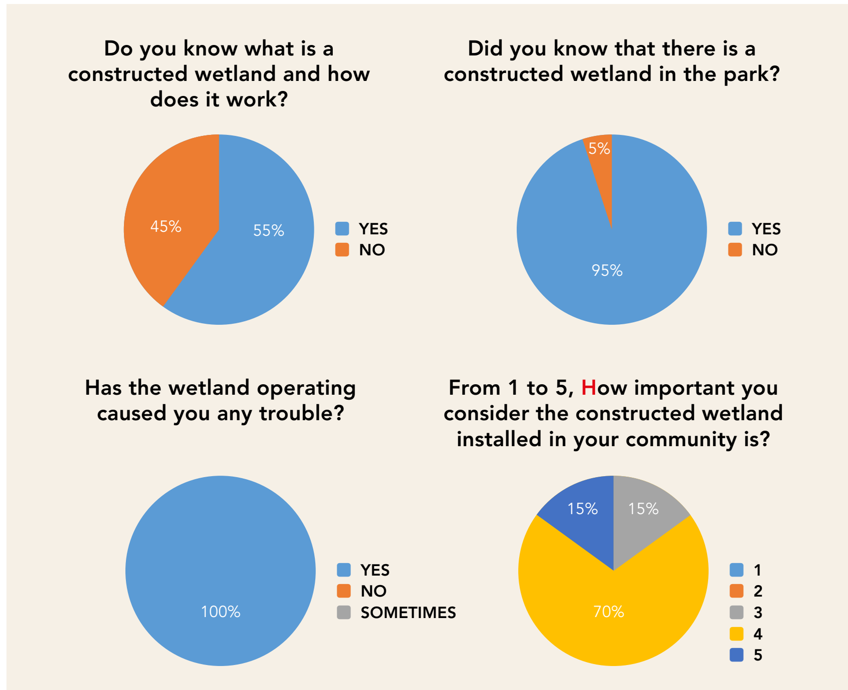


Figure 10: Knowledge the inhabitants have about the treatment system and its importance (Source: Garcia Rospigliosi, 2015)

7. Current Performance of the Park

After the inauguration of the project in August 2014, the LiWa team handed over the project to the neighbours and the local municipality. After the municipal elections in 2014 a new district administration took over in January 2015, only four months after the project inauguration, a new situation that was a threat for the park operation and maintenance. In 2015 all technical staff including the top management level were replaced as well as many maintenance workers and gardeners. The well-organised community La Florida II demanded the operation and maintenance of the new park by the municipality and presented the project to the new district administration. At the same time the LiWa project provided the means to employ a neighbour to overcome the transition period between the old and new administrations and the time with lack of maintenance from the municipal side. Later on the new municipality dedicated one worker for operation and maintenance, but with insufficient time as the person is in charge of the maintenance of several municipal green areas at the same time. Also there was limited training about the operation and maintenance provided. Currently one municipal worker is in charge of the operation of the pumping system and irrigation and is present almost regularly three times a week.

8. Lessons Learned and Conclusions

Many questions and constraints arise after implementing this project. The following points describe some reflections and the main lessons learned during and after the process:

- The project is located in a dynamic peri-urban area characterised by different social and environmental conflicts, changing conditions and uncertainties. These factors were a challenge during the design and implementation process.
- The irregular flow of water, characterised by an excess of water flow during the rainy season and scarcity and water use restrictions during the dry season, was a challenge for the constructed wetland design, testing and automation. For that the automatic operation of the treatment system could not be completed successfully and the irrigation needed to be operated manually by a person.
- The efficient irrigation system design is used only partially due to a lack of knowledge. Therefore the practice of flooding the green areas for irrigation continues.
- Safety remains a very important issue to consider when deciding on a technology. Surrounding areas are characterised by crime, and alcohol and drug abuse. These aspects have to play an important role when selecting the treatment technology and plant species. The height of the plans when fully grown has to be considered. The positive perception of the constructed wetland as an ecological treatment system could change in a negative way if dense vegetation becomes a hiding space for criminals. An incident of attempted attack was experienced and therefore the community decided to cut down the vegetation to a medium height.

The project is characterised by positive aspects and innovation:

- The implementation of a wastewater treatment plant in a public space is an innovative and unique case. On the basis of the questionnaires it could be assumed that the integration of a treatment system with recreational use was successful.
- The water quality monitoring shows that the water quality after the treatment process is significantly improved, reducing health risks to users of the park and reducing negative environmental aspects such as smell and the presence of vectors of waterborne diseases. Concerns remain about the presence of insects, which should be further investigated.
- Residents living close to the park have stated that they are aware of the potential health risk connected with the use of polluted water for irrigation and as a result they recognise the benefits of the treatment park. The residents also acknowledged that the landscape quality has improved considerably.
- The majority of survey respondents stated that the main problem was the lack of good management and operation in the park. The residents pay taxes to the municipality, which also include the maintenance of the green areas and public space. Therefore future conflicts can arise if local authorities do not take action to find

common solutions for green area maintenance. Better coordination among neighbours and municipal authorities is therefore needed.

- Since the project ended with the park inauguration, further scientific and social investigation is required to fully evaluate the park's performance, social acceptance, constraints, challenges, and benefits. A strong involvement of different actors, including local academia, is key for the creation and sharing of knowledge and providing comprehensive monitoring.
- Despite these conditions, the "Wastewater Treatment Park – Children's Park", is a lively place for children, women and men living in La Florida II and the surrounding areas. It would be necessary to investigate how to increase the treatment of polluted water for the irrigation of more green areas.
- The project represents the end of four years of research and a participative planning and design process with solutions and proposals for the more sustainable use of water resources in Lima and specifically in the Lower Chillon River Watershed, involving communities, metropolitan and local authorities, Peruvian and German academia, and researchers. As result of this experience, the LEIS Book was published as guidance for the application of WSUD on different scales, and the pilot project was built as a catalyst to show possibilities for the implementation of WSUD in different urban conditions, reusing different local water resources, such as insufficiently treated wastewater, black water, grey water, or contaminated surface water. The project was possible thanks to the community from La Florida II which has shown the power to co-lead the process and support the park design, construction, maintenance, and operation. In addition, the German Ministry of Education and Research (BMBF), the San Martin de Porres Municipality, and the community La Florida II co-financed the project with the aim of benefiting the community by gaining a new green space, which can support the reduction of socio-environmental conflicts in the area.

References

Akut Perú. 2014. *Manual del tratamiento de aguas de canal en humedal artificial WTL-ROTARIA para el uso en riego del parque en La Florida – Chuquitanta* (in Spanish).

Economist Intelligence Unit. 2010. *Latin American Green City Index 2010: Assessing the environmental performance of Latin America's major cities*. Munich, Germany: Siemens AG. Accessed February 2, 2016. https://www.siemens.com/entry/cc/features/greencityindex_international/all/en/pdf/report_latam_en.pdf.

Eisenberg, Bernd, Eva Nemcova, Rossana Poblet, and Antje Stokman. 2014. *Lima Ecological Infrastructure Strategy: Integrated urban planning strategies and design tools for water-scarce cities* (in Spanish). Stuttgart, Germany: Institute of Landscape Planning and Ecology. http://issuu.com/ilpe/docs/leis__-_esp_20141117_copy.

Fernández-Maldonado, Ana Maria. 2008. "Expanding networks for the urban poor: Water and telecommunications services in Lima, Peru." *Geoforum* 39(6):1884–1896.

García Rospigliosi A. 2015. *Sostenibilidad de un humedal artificial de flujo vertical, para el tratamiento de aguas contaminadas con fines de reúso. Avances del trabajo de tesis para título de Ingeniero Agrícola* (in Spanish).

Kosow, H., C. León, and M. Schütze. 2013. *Escenarios para el futuro – Lima y Callao 2040. Escenarios CIB, storylines & simulación LiWatool* (in Spanish). Accessed September 30, 2013. http://www.lima-water.de/documents/scenariobrochure.pdf.

LiWa Project. http://www.lima-water.de/.

Zapater-Pereyra, M., Eva Nemcova, and Rossana Poblet. 2014. "Ecological Infrastructure: Coupling wastewater treatment and open space design – Lima, Peru." In *IWA Specialist Group on Wetland Systems for Water Pollution Control Newsletter No. 45*, 30.

Note: The description of the project is based on the publication Lima Ecological Infrastructure Strategy (Eisenberg at al. 2014).

CASE 3

Wastewater Challenges and the Successful Implementation of Constructed Wetlands in Egypt (Egypt)

T. T. El-Gamal and M. H. Housian[1]

Abstract

With the gradual increase of water demand and the limitation of water supply, the feasible solution to meet water requirements in Egypt is through the reuse of different agricultural, municipal and industrial wastes. The Egyptian irrigation system is considered a closed system, where different water losses return to the drainage system, as well as a mixed system. This led to an increase in pollution in the drainage water, and it makes its reuse a serious problem. Providing sewage service and water treatment were among the main priorities of the government in recent decades. However, due to the economic challenges, the service did not catch up with rapid population growth. Therefore, it is important to find alternative solutions to mitigate the pollution problem that are economically and technically feasible. Constructed wetlands constitute a promising technique to face the problem. The technique was applied in Egypt on a large scale in northern lakes and on a small scale in some secondary drains (in-stream wetland). The pilot projects showed very promising removal efficiency for different pollution elements. In-stream wetland does not require additional areas, and as a simple and cheap technique, it could be applied in parallel at

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different sites, by incorporating non-governmental organisations, with a suitable dissemination and capacity programme, which could result in considerable progress in improving water quality, and help to save the use of wastewater.

Keywords: wastewater, reuse, pollution, economic challenges, constructed wetlands

1. Introduction

As a semi-arid region, Egypt suffers from water shortages, and the gap between water supply and water demand increases gradually with the rapid increase of the population. The ability to increase actual water resources from the River Nile became very limited and therefore the feasible solution to filling this gap is through dependence on the reuse of agricultural drains water and municipal wastewater. The majority of the cultivated area depends on gravity irrigation, which is normally associated with low water use efficiency. All agricultural water losses return to the system and they are mixed with sewage and industrial wastes, which return to the system as well. With the increase in municipal and industrial waste and the need to reuse such losses, water pollution became a serious problem.

The concept of reusing wastewater in Egypt dates back to the 1930s. However, intensive dependence began in the 1970s. Since this time, there was a gradual increase in dependence on drainage water due to the rise in water demand. At the same time, there was an increase in contamination of drainage and shallow aquifers with the rapid increase in population and the rapid change in living standards.

The limitation of economic resources affects the ability of the country to collect all municipal waste and treat it. More than 88% of rural areas do not have sewage services yet. They collect their sewage at sewage wells beneath the houses, which leak to the shallow aquifer. When these tanks are full, farmers dump the waste in the drainage or irrigation system through portable tanks. At many treatment plants in the cities, sewage effluent exceeded the capacities of these plants, and part of such effluent passes directly into different watercourses. The industrial waste is also dumped with primary treatment in many sites, and the capacity to improve all of this waste is economically difficult.

It is essential to investigate different alternatives in order to develop a solution that is feasible technically and economically and could be applied in a short time that fits with the rapid increase in population and the rapid change in living standards.

Many alternatives were investigated to help face the current water quality problem in Egypt. The wetlands technique is a promising technique in that regard. The low cost that falls to around one tenth of the regular treatment plants and the good results that were shown in some trials make such a technique one of the possible solutions to the water quality problem. The technique was already investigated in small spots, and the current challenge now is to investigate the ability to disseminate the concept and to incorporate non-governmental organisations in constructing and maintaining these sites.

2. Wastewater Reuse in Egypt

2.1. Current Water Balance in Egypt and the Importance of Reuse

Figure 1 shows the water balance in Egypt in 2010 based on the Egyptian water strategy for 2017 (August 2013). Total water resources were about 59.35 BCM, which mainly includes the share of the River Nile as well as small contributions from deep groundwater, precipitation and desalination. The Egyptian share of the River Nile has been constant since the treaty of 1959, while the population has increased around three times during the same period. The per capita share of water resources decreased significantly from a water surplus of 2,526 m3/capita/year in 1947 to a sufficient level of 1,972 m3/capita/year in 1970, and then water poverty with 663 m3/capita/year in 2013.

From Figure 1, water use in 2010 was 75.46 BCM (127% of water resources) with the effect of reusing water losses. This water use is distributed between the three consumption categories (agricultural, municipal and industry), and 34.8 BCM returns to the system. Final losses are 18.7 BCM, including 2.8 BCM that are evaporated and 15.9 BCM from the drainage water that are dumped to the sea, and the rest is reused.

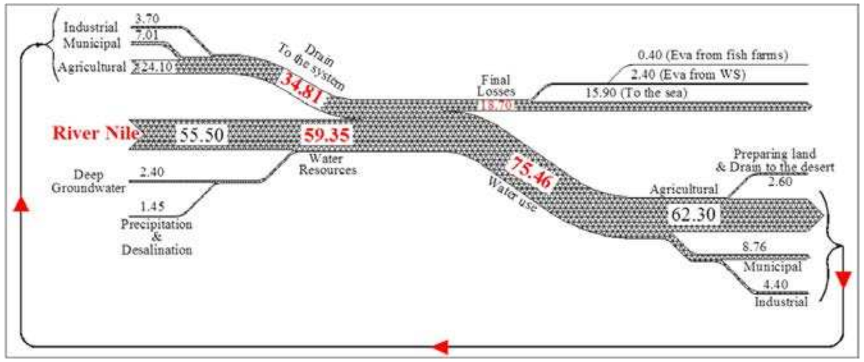

Figure 1: Water balance in Egypt in 2010 based on the Egyptian water strategy for 2017

The reuse has a positive effect on overall irrigation efficiency. Based on the previous Figure, and considering that total agricultural water consumption was 35.6 BCM, reuse increased overall efficiency from 57% to 74%. Other references estimated that overall irrigation efficiency increased from below 50% to 82% with the effect of reuse (R. J. Oosterbaan 1999).

The dependence on water losses increased gradually during recent decades as stated before. Figure 2 presents the gradual increase in the dependence on the drainage reuse in the last decades (Alam 2001). Alam (2001) stated that the unofficial use of drainage water by farmers is about 3.0 BCM/year and is rising rapidly with the increase in water crises.

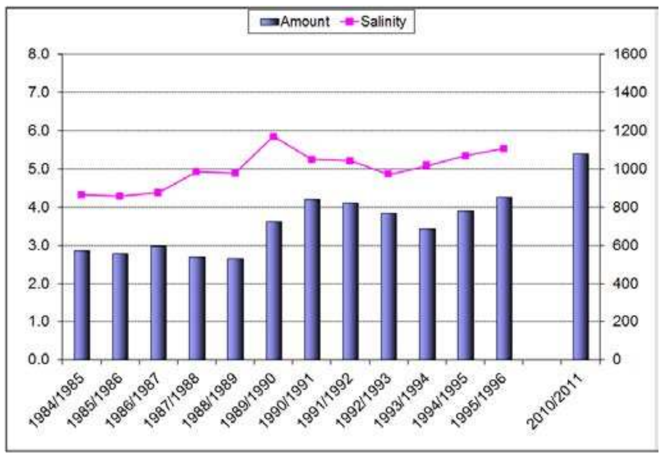

Figure 2: The dependence on drainage water reuse in Egypt during recent decades

2.2. The Side Effects of Reuse

Although reuse has a positive effect on increasing irrigation efficiency, many side effects have to be addressed. Salt accumulation is one problem, and salt balance is a crucial topic to be studied in Egypt. The salinity of the drainage water is increasing as can be observed from Figure 2, but the values were not critical yet. The important issue is the increase in biological contamination in different watercourses. With the rapid change in living standards, sewage effluent increased gradually, either from treatment plants, where the flow exceeded the capacity of these plants, or in rural areas, where the sewage is dumped directly into watercourses.

2.2.1. Pollution Sources (Point vs. Non-Point Pollution Source)

Normally, drainage water has different agricultural, municipal, and industrial waste. As a considerable portion of municipal and industrial waste is not treated, pollution increases gradually in this drainage water. Industrial waste reaches the drains at specific points (point source). Sewage is mixed with the drainage water either from point source (outlets of treatment plants) or through dumping sewage effluent into the drains from portable tanks as the majority of rural areas are not provided with sewage services yet. Figure 3 presents two examples for point and non-point pollution source in the Sabal drain in the Middle Delta. The figure on the right presents the outlet of a treatment station that dumps its wastes into the drain. The figure on the left presents portable tanks dumping raw sewage into the drain.

Figure 3: Dumping wastewater into waterways in Egyptian rural areas

Freshwater is contaminated when the drainage water is mixed with freshwater in the canals, and in a few cases sewage is dumped directly in the freshwater although this is prohibited.

2.2.2. The Contamination of Freshwater by Mixing with Drainage Water

Drainage water is mixed with freshwater in Egypt in two ways. Some drains dump their water into the Nile River and its branches. In addition, drainage water is lifted to the main or secondary canals through different lifting points.

The Nile course receives about 78 main agricultural drains discharging municipal, agricultural and industrial wastewater (El-Sherbini 1998). Normally, these drains have agricultural drainage water. During recent decades, many treatment stations were established and they dump their effluent into these drains. The treatment was primary and with the increase of the discharge beyond the capacities of these plants, some of the sewage passes without treatment. This led to a serious deterioration in water quality at these drains. The situation in the Rosetta branch presents a good example about pollution risks. The branch receives around 3.0 BCM/day of drainage water that is full of primary treated or untreated municipal and industrial waste trough five main drains (El-Rahawy, Sabal, El-Tahreer, Zaweit El-Bahr and Tala drains) and some factories that dump their waste in the branch (Ezzat et al. 2012). These drains receive domestic water from fifty-five towns and villages distributed along the branch. Ezzat et al. (2012) presented the effect of such drainage water on the water quality of the branch. For instance, the effect of El-Rahawy drains was assessed by measuring water quality in Rosetta before and after the junction with the drain. Ammonia ($NH3$) at the outlet of the El-Rahawy drain was 22.3 mg/l. In the Rosetta branch, the concentration was 3.6 mg/l before the junction with the drains and it increased to 8.35 mg/l after the junction with the drain. For Biological Oxygen Demand (BOD), the concentration at the outlet of one of these drains was 120.0 mg/l and it raised the BOD values in the branch from 5.0 mg/l before the drain to 52.5 mg/l after the drain. Water quality problems in the Rosetta branch have many serious effects, especially during the winter season with the decrease in freshwater in the branch, and one of these effects

is the death of fish in the branch. This happened many times and the last was in January 2016. On January 21, 2016, the official spokesman for the Ministry of Health and Population stated that the death of the fish was due to the increase in ammonia in the water, which led to a lack of dissolved oxygen, and therefore to fish suffocation. He stated that this was due to the untreated water of the El-Rahawy drain, which is full of chemical and biological contaminants (Youm7 newspaper, January 21, 2016).

Figure 4 presents the Rosetta branch at the point where the Sabal drain, which is full of sewage water, dumps its water into the branch. The two pictures on the left present the dead fish at the end of the branch in January 2016.

Figure 4: Rosetta branch at the junction point with the Sabal drain and dead fish at the end of the branch

2.2.3. Direct Dependence on Drainage Water

Suspending some lifting stations that lift drainage water to the main canals had a positive effect on the quality of these canals. However, and as the reuse is a part of the water budget in Egypt as explained before, this suspension, with the increase in demand, led to direct dependence on drainage water at the tail end of the irrigation network (northern areas). At many sites, the drainage water is highly contaminated. For example, there is a high dependence on the El-Gharibya main drain regardless of its bad quality. Based on the study by Egyptian and Japanese researchers (Satoh et al. 2016), ammonia in the drain was 29.4 mg/l, which is around 59 times the permissible value. The BOD value was 31.0 mg/l, or 3.1 times the permissible value. Total coliform was 1,632,000 CFU/100 ml, which is 326 times the permissible value.

However, there is a high dependence on this drain, either by lifting the water to some canals or from feeding back some canals, or directly by the farmers.

The continuous increase in demand with the expected reduction in water supply could lead to a serious problem in these areas.

Figure 5: Water at the tail end of two branch canals that receive feeding back from the Nashart and El-Gharibya main drains

3. Challenges and Solutions

3.1. The Characteristics of Irrigation and Drainage Networks

Most of the population of Egypt lives in the valley and the delta of the Nile, which constitutes around 3.5% of Egypt (around 35,000 km2). More than 4,600 villages and thousands of smaller entities (called ezba(s)) are scattered around this area. Most of the Egyptian cities are found in this area as well. The area looks like one cultivated land area served by thousands of nested irrigation canals from different levels. More than 50,000 km(s) of irrigation and drainage canals cover this area in a very dense system. Most of the rural areas were not provided with sewage services, and therefore the sewage in this rural area is collected and dumped in drainage and irrigation systems. It appears that farmers have no other feasible solutions unless other interventions are developed and disseminated among them.

3.2. The Economic Challenge

Addressing the pollution was among the main targets of the government of Egypt during recent decades. Based on the Information Memorandum, October 6 Wastewater Treatment Plant Project (2009), the investment in sewage treatment in Egypt increased from 0.8 billion LE in 1982 to 40.0 billion LE in 2007. During the same period, the total treated water increased from 1.1 MCM/day to 11.0 MCM/day, or from 25 l/capita/day to 150 l/capita/day. However, and based on the same reference, the coverage level for sewage services in 2007 was 60% of cities and 4% of rural areas. It should be noted that the sanitation service arrived around 10 years after providing rural areas with drinking water. Providing rural areas with drinking water was associated with a considerable change in municipal water use and consequently in sewage effluent. Municipal requirements increased around three times, from 3.1 BCM in 1990 to 6.57 BCM in 2005 to 8.76 BCM in 2010, and they are estimated to reach 11.4 BCM in 2017. In 2010, and from 8.76 BCM, 7.0 BCM return to the system, and 3.6 BCM from them are untreated. Regardless of the considerable effort to provide the areas with sanitation services, the progress is slower than the increase in the population. Abdel Wahaab and Omar (2013), stated, "In spite of continuous government efforts to extend water services to all urban and rural populations, the service does not catch up with rapid population growth, and hence service coverage is worsening."

Regarding the required cost, it was stated by officials that the cost of providing sewage services for all villages is almost 100 billion Egyptian Pounds. Abdel Wahaab and Omar (2013) stated that the average cost of treating a cubic meter of sewage in Egypt is almost 5000 LE. Operation and maintenance (O&M) costs are 15% of the investment cost. Riad (2004) stated that the partial treatment of sewage costs the government some 600 million Egyptian Pounds. Such large investments might not be feasible considering the current economic situation in Egypt. Therefore, cheap and simple techniques should be investigated.

3.1. Solutions to Address Water Quality Problems in Egypt

The direct way, which depends on the collection of sewage and establishing new treatment plants, is the current official way to face the pollution problem in Egypt. Other techniques were tested as research activities or pilot projects on a small scale. Some of these ideas are presented here.

One of these alternatives was to use the polluted water in constructing artificial forests. A pilot project was conducted to cultivate thirteen regions (2,700 hectares) in different Egyptian governorates (Riad 2004). Two problems are associated with this approach. The first challenge is the characteristics of irrigation and drainage networks in Egypt as presented before. The dense and nested networks that are surrounded with the cultivated areas make such a technique suitable for specific drains at the border of the Nile Delta. The second challenge is the risk of changing to feeding crops. Low cultural levels with a substantial difference in the return from cultivating different crops could lead to such a change. A clear example about using contaminated water in cultivating normal crops was found in the El-Saf canal. The canal receives bilateral treated wastewater from some treatment plants in addition to industrial wastewater. It was planned to use the canal to plant forest trees or some crops that are suitable for the water quality in the canal. Currently, instead of planting forests tree, more than twenty thousand acres have been cultivated with traditional crops and vegetables and they use the surface irrigation method. This will probably lead to terrible health problems.

The second alternative was the reuse of agricultural drainage water from collectors and farm drains before mixing it with polluted water in the main drains. The idea was discussed by the Ministry of Water Resources and Irrigation, but the actual implementation has not yet taken place. Using a ratio of agricultural drainage water before dumping in the main drains means that contamination in the main drain will increase and using it will become harmful.

The third technique was the wetlands that were successfully applied in many regions in Egypt. The technique is very promising and it will be discussed in more detail.

3.4. Use of Constructed Wetlands as a Solution

Based on El-Torkemany (2009), using "Constructed / Engineered wetland" dates back to 1905 in Australia, and it was limited until 1950, when Europeans began to use it in Germany. Americans began using it in 1970. Now thousands of wetlands are distributed all over the world. In such wetlands the plants, through their roots, stems and leaves, are an ideal place to break down the organic matter in the sewage. The technique is suitable for small and moderate villages.

El-Torkemany defined the advantages of this technique as low construction and operation costs with efficient removal ratios. In addition, the plants used in the wetland could be used after harvesting to feed livestock. The main disadvantage is the large amount of space required for this technique compared to traditional treatment plants.

In Egypt, the technique was used in two ways: the first type was applied at the farthest end of the drainage network. The wetlands were constructed in Lake El-Manzala on the northern shore of Egypt, which receives highly polluted water from some main drains. The other type (in-stream wetlands) was applied at the beginning of the drainage network and was used in small drains. In both types, the results were very promising.

For the wetlands in the northern lakes, the project was implemented by Egypt's Ministry of Environmental Affairs with a contribution from UNDP, and was handed over as a fully operating facility to the Ministry of Water Resources and Irrigation. The treated water was used for irrigation and agriculture, and a portion was diverted into basins designed for fish farming. The total flow to the wetland was 25,000 m3/day. The system costs just 10 percent of traditional, chemical-intensive wastewater treatment systems, and the treatment level was considerably high. The removal efficiency exceeded 60% of Biological Oxygen Demand (BOD), 80% of Total Suspended Soil (TSS), 50% of Total Nitrogen (TN), and 99% of Faecal Coliform and Total Coliform (Higgins et al 2001).

3.5. In-Stream Wetlands

The second type (in-stream wetlands) is discussed in more detail. The technique is normally applied in small drains at the beginning of the drainage network. Besides the general benefits of wetlands, in-stream wetlands have two main advantages:

- The technique does not require additional areas. This is a general drawback for wetlands, especially in Egypt as all lands around drainage network are highly valued lands.

- Working with small sizes gives a chance for the involvement of non-governmental organisations in operations and maintenance, and even in the construction of such wetlands. With good dissemination and capacity building programmes, isolated villages, through any non-governmental organisations in these villages, could take the lead and work in parallel at different sites, which could have significant progress in improving water quality.

Many in-stream wetland experiments were conducted, and some of them are presented here:

Abbel Bary et al. (2003) tested the effect of a natural aquatic treatment system (water hyacinth) in improving agricultural drainage water. They investigated the technique in the Sabal drain, which is one of the main pollution sources of the Rosetta branch. Natural water hyacinth can reduce BOD by 37%, and TSS by 80%. Treatment efficiency ratios for ammonia (NH_3) and nitrate (NO_3) were 14% and 2%.

Abou-Elela et al. (2014) investigated the effect of planted and unplanted constructed wetlands for removing different pollutants. According to the authors, planted wetlands proved to be an efficient technology for the removal of both physiochemical and biological pollutants. The COD, BOD and TSS removal rates reached 88%, 91% and 92%, respectively. A high-percentage removal of microbiological parameters was achieved in the planted unit compared with the unplanted one, which indicates the positive role of plants in bacteria removal from wastewater. The unplanted unit proved to be efficient in the removal of COD, BOD and TSS, but it lacked efficiency in the removal of pathogens and nutrients.

Rashed and Adbel Rasheed (2008) investigated in-stream wetlands in two small drains: the Faraa Al-Bahow drain in the East Delta, and the Edfina drain in the West Delta. The first experiment is presented in detail as an example of achieving high treatment efficiency using a in-stream wetland.

Based on Rashed and Adbel Rasheed (2008), the Faraa Al-Bahow drain is a small drain that has a length of 1,710 m and a served area of 533 hectares. Inside the served area, there is a small rural community of 3,000 people, supplied with potable drinking water with small pipe network collecting raw sewage wastewater and dumping it into the Faraa Al Bahow drain inlet without treatment. The Faraa Al-Bahow drain empties its water into a higher drain (Al-Bahow) that serves 2,100 hectares. The area suffers from water shortages during the summer season, which force farmers to depend on the drainage water. Therefore, the low quality of the Al-Bahow drain has a serious effect on the farmers. The in-stream wetlands in the Faraa Al-Bahow drain are:

- A sedimentation pond (100*2*1 m);
- A wooden gated weir and a steel plants screen that governs a series of floating (150*3*0.5 m);
- Emergent aquatic plants (150*3*0.5 m) reaches;
- A control weir at the drain outlet; the function of the weir is to control drain water depth and treatment detention time according to pollutant loads.

The system as presented by the author consists of five components, which are sedimentation, filtration, biodegradation, nutrient plants uptake, and pathogen eradication. Sunlight penetration enhances oxygen content and water disinfection. The vegetation system consists of common reeds (Phragmites Australis) and floating water hyacinth.

The results presented by Rashed and Abdel Rasheed (2008) illustrated the effect of different parts of the in-stream wetland in removing different pollution elements. TSS was removed mainly inside the sedimentation pond where TSS fell from 915 to 114 mg/l. TSS reached 20 mg/l at the drain outlet. BOD decreased from 550 to 32 mg/l before wetland cells, and reached 7 mg/l at the drain outlet. Pathogens (TC and FC) were perfectly treated along the drain path. Total coliform was reduced from 4.E+07 TCU/100 ml at the inlet to 2.E+06 TCU/100 ml after 800 m and then 7.E+04 TCU/100 ml through in-stream cells and finally reached 5.E+03 at the drain outlet. Faecal coliform has similar results to total coliform.

The treatment efficiencies for TSS, BOD, TC and FC were 97.8%, 98.7%, 99.9%, and 99.9%, which are very promising results.

4. Conclusion and Future Studies

Pollution is a severe problem in Egypt. With the limitation of water resources, the reuse of water losses became the feasible solution to meet water demand. Such losses contain different agricultural, municipal and industrial waste. The treatment level is relatively low, and therefore such losses are highly contaminated. The main concern is the savings in using these available losses. Collecting and treating all municipal and industrial waste requires high levels of investment, which are not available considering the current economic situation in Egypt. It is important to figure out a solution that is feasible technically and economically. Wetland is a good candidate to face such a problem. The technique was applied on two different scales in Egypt. The bigger scale was applied in the northern lakes and the smaller scale was applied in some secondary drains (in-stream wetland). In-stream wetland is a promising technique to face water quality problems in Egypt. The pilot projects that were conducted reported good removal efficiency for different pollution elements. In addition, in-stream wetland has some characteristics that make it more suitable for Egypt. The technique does not require additional surface areas and employs a simple technology. Isolated villages, with the help of any non-governmental organisations in these villages, could take the lead and work in parallel at different sites, with a suitable dissemination and capacity programme. This could result in substantial progress in improving water quality.

The key issue therefore is to investigate the ability to incorporate non-governmental organisations in establishing and operating such sites. This should be built on a deep understanding of their situations and how to build their capacities. Water user associations should be at the forefront of these organisations and operating such sites should be among their roles in maintaining different irrigation and drainage properties. The studies should also investigate how to enhance the capacities of these organisations to achieve an efficient and sustainable system.

References

Abdel Bary, M. Rafeek, Abdelkawi Khalifa, M. Nour Eldin, Ashraf M. Refaat, Maha M. Ali, and Zeinab M. El-barbary. 2003. "Wetland as Pollution Control Treatment System for Agricultural Drains." Paper presented at the seventh International Water Technology Conference, Egypt, April 1–3.

Abdel Wahaab, Rifaat and Mohy El-Din Omar. 2013. *Wastewater Reuse in Egypt: Opportunities and Challenges*.

Abou-Elela, Sohair. I., G. Golinelli, Abdou Saad El-Tabl, and Mohammed S. Hellal. 2014. "Treatment of municipal wastewater using horizontal flow constructed wetlands in Egypt." *Water Science & Technology* 69(1):38–47.

Alam, M. N. 2001. *Water and agricultural lands in Egypt*. Cairo, Egypt.

El-Sherbini, A. M. 1998. "Quality of agricultural wastewater disposed into Rosetta Branch." Proceeding of Arab Water 98, Cairo International Conference Center, Cairo, Egypt, April 26–28.

El-Torkemany, A. M. 2009. *Constructed Wetlands: Plan, Design and Construction Guide*. http://www.4enveng.com/userfiles/file/CWs%20Plants%20Guid.pdf.

Ezzat, Safaa M., Hesham M. Mahdy, H. M., Mervat A. Abo-State, Essam H. Abdel Shakour, and Mostafa A. El-Bahnasawy. 2012. "Water Quality Assessment of River Nile at Rosetta Branch: Impact of Drains Discharge." *Middle East Journal of Scientific Research* 12(4):413–423.

Higgins, John. M., D. El-Qousey, A. G. Abul-Azm, and M. Abdelghaffar. 2001. "Lake Manzala Engineered Wetland, Egypt." Wetlands Engineering & River Restoration Conference, August 27–31, Reno NV. doi:http://dx.doi.org/10.1061/40581(2001)49.

Ministry of Housing, Utilities and Urban Development/PPP Central Unit. 2009. *6th of October Wastewater Treatment Plant Project, Information Memorandum*. http://www.pppcentralunit.mof.gov.eg/SiteCollectionDocuments/PPPCUSite/Info%20memo.pdf.

Ministry of Water Resources and Irrigation. 2013. Redeveloping the National Plan of Water Resources – Water Strategy until 2017 (in Arabic), August. Cairo, Egypt: Ministry of Water Resources and Irrigation.

Oosterbaan, R. J. 1999. "Impacts of the Irrigation Improvement Project on Drainage Requirements and Water Savings." Report to the Egyptian-Dutch Advisory Panel on Land Drainage and Drainage Related Water Management of a short-term consultancy mission.

Rashed, Ahmed and Adel Adbel Rasheed. 2008. "Polluted Drainage Water Natural On-Stream Remediation." Paper presented at the 26th Annual Water Treatment Technologies Conference, Alexandria, Egypt. Volume: 26.

Riad, Mamdouh. 2004. *Innovative Approach to Municipal Wastewater Management: The Egyptian Experience*. Egypt: Ministry of State for Environmental Affairs. http://www.unep.org/GC/GCSS-VIII/Egypt-sanitation.pdf.

Satoh, M., El-Gamal, T., Taniguchi, T., and Xin, Y. 2016. "Water Management in Nile Delta." In *Irrigated Agricultural in Egypt, Past, Present and Future*, edited by M. Satoh and S Aboulroos.. Springer (forthcoming).

Youm7. 2016. http://www.youm7.com/story/2016/1/21/2549336/.

CASE 4

Use of Reservoirs to Improve Irrigation Water Quality in Lima, Peru (Peru)

Julio Moscoso Cavallini[1]

Abstract

Due to the discharge of untreated domestic wastewater into rivers and the increasing scarcity of water, the use of contaminated water is a reality that urban and peri-urban farmers in areas close to big cities have to take into account. This vicious circle is closed by offering these cities contaminated food that causes serious health problems to the poorest and therefore most vulnerable population. Efforts to achieve the Millennium Development Goals of reducing by 50 per cent the number of people without a supply of safe water and appropriate sanitation by 2015 could increase the problem described above if the treatment of wastewater does not go hand in hand with all these efforts. Meanwhile, there is a need to seek immediate alternatives that reduce the contamination of water used for irrigating agricultural products such as vegetables.

Against this background, the International Potato Centre (CIP) Urban Harvest Programme evaluated the quality of water in the basin of the river Rímac to quantify impacts on irrigation water, soil and vegetables and to assess a reservoir-based treatment system to improve the quality of water and vegetables produced in the area. Studies carried out between 2005 and 2007 confirmed that irrigation water in this

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important agricultural area is strongly contaminated with parasites and faecal coliforms. The concentration of faecal coliforms is more than 5,000 times higher than the permitted limits for water used to irrigate vegetables. As a result, more than 30 per cent of these vegetables are not fit for consumption.

Figure 1: First reservoir built in east Lima

The implementation of water treatment systems based on the use of reservoirs made it possible to promote agriculture irrigated with good quality water, sustaining the production of healthy vegetables that do not harm consumers' health. Storing river water for more than 10 days enabled the total removal of human parasites and a reduction in fecal coliforms down to the levels set by the law on the irrigation of vegetables. Reservoirs also enable greater productivity and profitability for vegetable cultivation, compensating for the use of land and the investment made to install them. The extra earnings from the production of fish improved profits and better justified the investment effort by farmers to build new reservoirs.

An evaluation conducted in 2013 by the Pan American Health Organization (PAHO) and the General Directorate of Environmental Health (DIGESA) confirmed that six years later, the quality of water from the reservoirs is still good for vegetable cultivation and that farmers are continuing to breed fish to feed their families. Moreover, these agricultural products sell at the best prices.

Keywords: pollution, irrigation water, vegetables, quality improvement, reservoirs

1. Background

The rapid increase in the population of Lima, currently home to 9.8 million people, (National Institute of Statistics and Information Technology, INEI, 2015) is leading to the unplanned growth of informal settlements that do not have urban services such as waste management, drinking water, and sewerage systems. This situation generates the discharge of large volumes of liquid waste that have a negative impact on surface water bodies used for agriculture and other purposes and affect the health of urban residents. Agricultural producers and the consumers of locally produced food are at a high risk of contracting certain waterborne diseases. The scarcity of water and the lack of adequate treatment for domestic wastewater mean that the use of contaminated water is a common practice in urban and peri-urban areas. Like Lima, other cities in the world located next to rivers have the same environmental problems of nutrient overload and contamination by pathogens and toxic chemicals that affect the ecosystem and public health.

Agriculture in the eastern part of Lima produces more than 15 per cent of the vegetables consumed by the city. Water from the river Rímac is used to irrigate these crops, but it is contaminated by untreated domestic wastewater from settlements, discharged into the lower part of the basin before it is used for irrigation. Informal settlements of this type are also located around the agricultural area, worsening the pollution of these waters.

In 2004, against this background, the Urban Harvest Programme conducted by the International Potato Centre (CIP) formed an alliance with the Pan American Health Organization (PAHO), the River Rímac Users' Council, the municipality of Lurigancho-Chosica, and farmers from the area. This alliance had the financial support of the Community of Madrid-CESAL to: a) evaluate the quality of water in the river Rímac basin and quantify impacts on irrigation waters, soil and vegetables produced in the East Cone of Lima, and b) evaluate an innovative treatment system based on simple reservoirs to improve the quality of water used in the production of vegetables, using these environments for fish farming as an economic option for farmers (Moscoso et al. 2008). After completion of the project in 2007 there was no further monitoring for the next six years. Only in 2013 was a new assessment made of the water, soil, vegetables and fish of this agricultural area, taking advantage of testing for the Sanitation Safety Planning Manual (SSP) conducted by the World Health Organization (WHO) in several countries of the world, which included as one of its agricultural case studies this agricultural

Figure 2: Location of the agricultural area in the east of Lima

area of east Lima. These SSPs are supported by the identification of risk focuses recommended in a step-by-step process to facilitate implementation of the WHO Guidelines 2006. Intensive monitoring of this case was conducted by the Pan American Health Organization (PAHO) and the General Directorate of Environmental Health (DIGESA) of the Ministry of Health of Peru (PAHO 2014).

2. Methodology

The study was conducted in three stages. The first two were in 2007 and comprised the following activities:

- Evaluation of the quality of water in the river Rímac basin and impacts on irrigation waters, soil and vegetables.
- After construction of the first reservoir, an assessment was made of water and vegetables irrigated with irrigation channel and reservoir water and of the fish bred in the reservoir.

The third part was carried out six years later in 2013 and consisted of an assessment of water quality, some vegetables and the fish farmed in the reservoirs of the agricultural area.

2.1. Evaluation of Historical Data about the Water Quality of the River Rímac

As preliminary work, an evaluation was conducted using historical data concerning the water of the river Rímac, information mainly based on the monitoring programme conducted over several consecutive years by the Lima Potable Water and Sewerage Service (SEDAPAL) and the General Directorate of Environmental Health (DIGESA) of the Ministry of Health. The parameters chosen were arsenic (As), cadmium (Cd), chromium (Cr) and lead (Pb) as these are the toxic elements that, due to bioaccumulation, have the greatest impact on public health. Faecal coliforms were used as an indicator of faecal contamination, covered in the World Health Organization Guidelines for the use of wastewater in agriculture and aquaculture (WHO 1989).

2.2. First Evaluation of the Quality of Water, Soil, and Agricultural Products

A detailed study was carried out on the quality of water, soil, and agricultural products in the agricultural areas of Carapongo, Huachipa and Nievería. These locations were chosen due to 50, 33 and 28 per cent of occupied areas being dedicated to vegetable growing.

Between 2004 and 2005, 45 water samples were taken from irrigation channels in the agricultural areas of Carapongo, Huachipa and Nievería. Sampling points included intakes, main channels, branch channels, side channels and possible contamination points in the irrigation system.

The parameters chosen to evaluate the quality of vegetables were As, Cd, Cr, Pb, faecal coliforms and human parasites. Between 2004 and 2006 32 samples of the main vegetable crops were taken: huacatay (*Tagetes minuta L.*), lettuce (*Lactuca sativa L.*), radish (*Raphanus sativus L.*), turnip (*Brassica rapa L. var. rapa*), beet (*Beta vulgaris L. var. Crassa*) and celery (*Apium graveolens L.*). Sampling was also done of perennial ryegrass (*Lolium perenne L.*) as it has been very widely grown in these areas in recent years. At harvest time, five or six subsamples were taken to form a composite sample. The vegetables were classified according to the location of the edible part, i.e.: roots (turnip, radish and beet) or foliage (lettuce and huacatay). Samples were collected before and after washing from beet, huacatay and radish prior to these products being put on sale.

Soil samples were obtained from the surface 20 cm in the same place as where the vegetable samples were taken. Five or six subsamples were also taken to form a composite sample.

2.3. Criteria for the Design of Reservoirs

The experimental reservoir at Carapongo was built to confirm if storing river water for more than 10 days enabled the total removal of human parasites and a reduction in faecal coliforms down to the levels set by the Regulation on the irrigation of vegetables. In practical terms, it was proposed to use 50 per cent of the volume stored, thus leading to an expected theoretical retention time of approximately two weeks. After agreeing with the farmer to water a 2,000 m^2 plot, a calculation was made of the water requirement for such a plot, bearing in mind that the watering frequency (WF) is every four days in summer and every seven days in winter.

2.4. Evaluation of the Improvement in Water Quality and Crops through the Use of Reservoirs

During the first four months of operation of the Carapongo reservoir (April to July 2005) the first experiments were conducted on radish and lettuce crops in two similar plots of 500 m^2 each, one of which was irrigated with water straight from the irrigation channel, while the other had water taken from the reservoir. A subsequent experiment on a combined crop of beet and radish was conducted between August and November 2005.

The safety of water from the channel and from the reservoirs used for irrigation was analysed monthly, using the parameters of human parasites and faecal coliforms. The analyses conducted on harvested products determined the concentrations of faecal coliforms and human parasites detected on them.

The improvement in agricultural productivity was evaluated by comparing the incomes and costs for the plots irrigated with channel water and those irrigated by reservoir water. The differences in income were attributed to the benefit of the reservoir and a determination was made of capacity to pay the debt incurred through building the reservoir expressed as the number of cropping seasons required to pay for the investment.

2.5. Evaluation of Supplementary Fish Production

Fish farming in the reservoirs was proposed in order to compensate for the loss of agricultural land for building the reservoir and to provide families with an additional source of nutrition to consume or sell. In April 2005, a combined population of 3,000 grey and red Nile tilapia alevins were placed in the first reservoir at a density of 20 alevins/m^2. In late November 2005, 1,450 juvenile tilapia were placed in the second reservoir. In January 2007, 5,000 tilapia alevins were placed in the third reservoir. In the latter two cases fish were placed at 3 fish/m^2.

Figure 3: Monthly monitoring of fish weight

The fish were fed on a concentrate for tilapia. The temperature of the water was recorded daily and the weight of the fish was monitored every month to see how much they had grown depending on the temperature.

2.6. Second Evaluation of the Quality of Water, Soil, and Agricultural Products

Support from the World Health Organization for the development of the Sanitation Safety Plan for the agricultural area of Lima East made it possible, six years later, to conduct intensive monitoring to check on the quality of water, soil, grass and vegetables irrigated with water from the river and from the reservoirs, as well as the fish bred in them. The sampling plan for these items included the following parameters:

- Chemical parameters in water: Suspended solids (SS), biochemical oxygen demand (BOD5), N-total, P-phosphates, salinity and heavy metals (As, Cd, Cr, Pb and Hg)
- Health parameters in water: thermotolerant coliforms (faecal), human parasitic nematodes and protozoa
- Physical-chemical parameters in soil: pH, organic matter, nitrogen, phosphorus, potassium, salinity and heavy metals (As, Cd, Cr, Pb and Hg)
- Health parameters in soil: thermotolerant coliforms (faecal), human parasitic nematodes and protozoa
- Chemical parameters in soil: heavy metals (As, Cd, Cr, Pb and Hg)
- Health parameters in grass and vegetables: thermotolerant coliforms (faecal), human parasitic nematodes and protozoa
- Health parameters for fish: aerobic mesophiles, Escherichia coli, Salmonella spp, Staphylococcus aureus and human parasites

Between October and December 2013, 230 water, soil and grass samples were taken in three assessment areas on three sampling dates: October 21, November 11 and December 9, 2013. In addition, two sampling exercises were conducted in January 2014 to evaluate five types of vegetable and the fish from two reservoirs.

3. Results and Discussion

3.1. Quality of Water from Irrigation Canals

No water sample exceeded the maximum permitted limits for As, Cd, Cr or Pb set in the regulations for the cultivation of vegetables. This shows that the water currently used for watering vegetables does not represent a risk of contamination by these metals.

Nevertheless, the contamination of river water with pathogens is the most serious problem for vegetable production. As shown in Figure 4, more than 97 per cent of samples of water taken from the irrigation channels were far above the maximum permitted limit for faecal coliforms and some samples contained more than 5 million MPN/100 ml. The river Rímac is one of the main sources of faecal contamination, but there is also a contribution from the settlements around the vegetable-growing areas, which tip their wastewater and sewage directly into the irrigation channels.

Figure 4 also shows the levels of contamination by human parasitic nematodes and protozoa in the irrigation channels. The Carapongo intake receives water with more than 25 parasites per litre, a similar concentration to that in most of the sampling points evaluated in this irrigation system. The Nievería intake, on the other hand, receives parasite-free water, a situation which deteriorates when it receives drainage waters from Carapongo. In general, contamination levels reach 25 parasites per litre in Nievería and Huachipa.

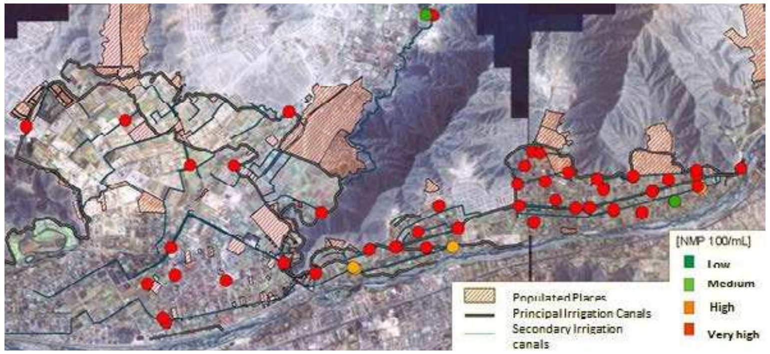

Figure 4: Level of faecal coliforms and parasites in the water of the Lima East irrigation channels (Source: Moscoso et al. 2007)

3.2. Quality of Vegetables Irrigated with River Water

Chemical analyses indicate that vegetables are grown in areas affected by arsenic and lead; in spite of high levels of lead in the river basin, however, the levels found in soil and crops were not high enough to suppose a risk to health. Analysis of some of the vegetables showed that there was much greater absorption of cadmium and lead in leafy (foliage) crops than in root vegetables, but only the huacatay was above maximum permitted levels. This herb is used in small quantities to season various Peruvian dishes and for this reason it would not pose a serious risk to health.

Analysis of lettuce and radish, both of which are eaten raw, showed that between 17 and 31 per cent of samples were above permitted limits for faecal coliforms. In addition, the practice of washing products in irrigation channels increases contamination. Fifty-seven per cent of good quality vegetables were contaminated during washing (Figure 5). Actions such as washing vegetables with clean running water could considerably reduce the contamination of these foods with pathogens.

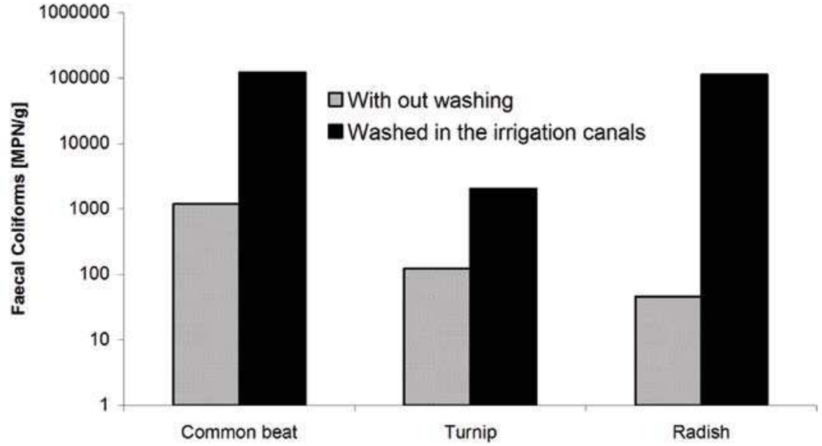

Figure 5: Effect of washing vegetables in irrigation channels (Source: Moscoso et al. 2007)

It was also found that leaf crops such as lettuce and huacatay, and even perennial ryegrass, present higher levels of parasites than root crops such as turnip, radish and beet, as shown in Figure 6. This greater presence of parasites in foliage plants could be attributed to direct contact with contaminated water, whereas for root crops the water passes through the soil which, to a certain extent, acts as a filter. Concentrations above 24 parasites/g (nematodes and protozoa) found in lettuce merit special attention since lettuce is eaten raw.

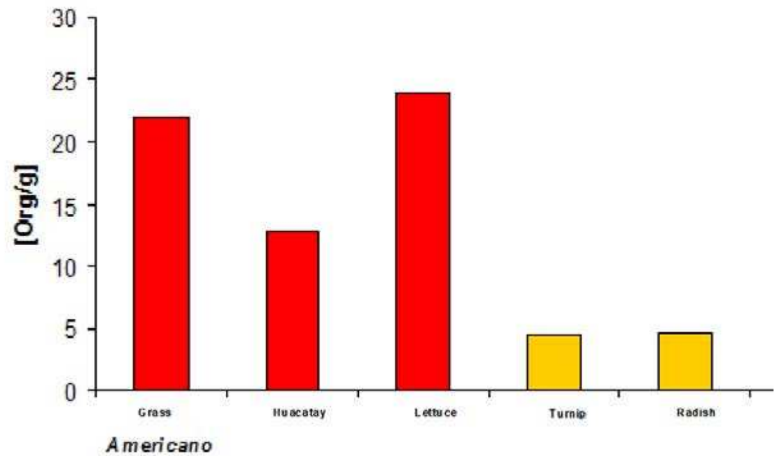

Figure 6: Concentration of parasites by type of crop (Source: Moscoso et al. 2007)

3.3. Low-Cost Reservoirs to Reduce the Contamination of Vegetables

Given that heavy metals were not a problem in this agricultural area, the study focused on the need to address the high levels of faecal bacteria and parasites, mainly from untreated domestic wastewater discharged into the river. The ideal way to improve the quality of water for irrigation and washing would be to eliminate the discharge of untreated domestic wastewater. There are, however, no plans in the short term to implement such sanitation services in this area.

The construction of small treatment reservoirs was identified as a viable option to reduce pollutants in irrigation water. Water treatment in these reservoirs is fairly simple, based on both the time required for physical processes to act on pathogens and on meeting farmers' needs for irrigation and other practices. Water arrives at the reservoir through the channels and remains there for approximately 10 to 14 days. Retaining the water for more than 10 days reduces the concentration and viability of pathogenic bacteria, a process that is strongly influenced by solar radiation and temperature variations. Moreover, parasitic nematodes settle on the bottom where they gradually die, leaving the water clean for vegetable irrigation. These reservoirs were also designed for fish farming. It was estimated that 50 per cent of the volume would be used per week, allowing a retention period of 14 days to be achieved with maximum volume, sufficient to reduce contaminants in irrigation water.

Samples of water treated in reservoirs and contaminated river water were compared when used for irrigating radish and lettuce. The results showed that storing it in reservoirs removed 98 per cent of faecal coliforms and eliminated virtually all the human parasitic nematodes and protozoa from the irrigation water. Water quality changed from being well above the maximum permitted limit of 1,000 faecal coliforms per 100 ml for vegetables (water taken directly from the river) to being below these maximum limits when the water was stored in a reservoir (Figure 7).

Radish and lettuce grown with both sources of water were also evaluated, showing that crops irrigated with reservoir water had up to 97 per cent fewer coliforms (between 10 and 100 faecal coliforms per gram), placing them below the permitted limits, as was the case for human parasitic nematodes and protozoa, which were virtually absent from both radish and lettuce.

What is more, irrigation with reservoir water seems to have had a beneficial effect on the growth rate and uniformity of the harvest,

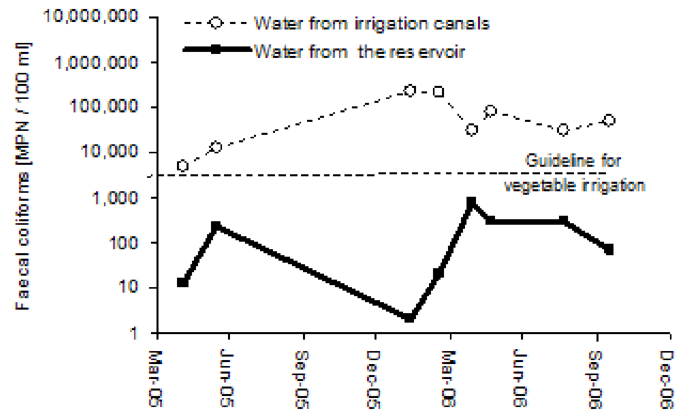

Figure 7: Concentration of faecal coliforms in irrigation channel and reservoir water (Source: Moscoso et al. 2007)

since a greater percentage of marketable products was achieved than with those irrigated with river water. This low-cost, simple technology captures nutrients in irrigation water in a biomass of microalgae that can then be reused to achieve higher vegetable production.

The evaluation established that to obtain water of sufficient quality to irrigate one cropped hectare, a 700 m^3 reservoir is required at a cost of US$1,360 if it is waterproofed with a soil-cement mixture. Alternative coatings are compared in Table 1. If the reservoir is connected to a multi-gate irrigation system, the water requirement can be reduced by 50 per cent.

Table 1: Options for Waterproofing Reservoirs

	Area (m^2)	US $/$m^2$
Simple concrete, f'c=140 kg/cm^2	232	7.97
Geo membrane HPDE Thickness 1 mm	232	5.82
Geo membrane HPDE Thickness 1 mm	714	5.82
Geo membrane HPDE Thickness 1 mm	1350	3.76
Soil – Cement (2.4 kg /m^2)	1350	0.49
Soil – Cement (2.4 kg /m2)	1350	0.12

Source: Moscoso et al. 2007

3.4. Fish Production

A disadvantage of using reservoirs is that they occupy potentially productive land in these peri-urban areas, where land values are very high. For this reason, it was proposed that these small reservoirs be used as aquaculture systems to compensate for the loss of farmland and to provide the family with fish as an additional nutritional source to eat or sell.

Figure 8: Tilapia harvested in reservoirs

Preliminary results were quite satisfactory for the farming of Nile tilapia (*Oreochromis niloticus*). Tilapia is a tough species that is very well accepted by the local population. In subtropical climates such as that of Lima, the growth rate of Nile tilapia during the warmer months is encouraging and similar to that achieved in tropical climates. Many sexually reversed tilapia with a starting weight of under 2 g can be bred throughout the year in densities of three fish per m^2, reaching a commercially acceptable size of 250 g by the end of the summer. With 450 kg of fish food, 400 kg of tilapia were produced in a 500 m^2 reservoir, with a productivity greater than 0.73 kg/m^2. The estimated cost of alevins and food was US$470, which enabled a sale income of US$880.

3.5. Second Evaluation of the Quality of Water, Soil, and Agricultural Products

Results of the water safety analyses are shown in Table 2, with the addition of Environmental Quality Standards for Natural Waters (ECAs) issued by the Ministry of the Environment (Supreme Decree 002-2008-MINAM).

The Peruvian Water Quality Standards (ECAs) establish that natural water used for irrigating vegetables must not have more than 15 mg of BOD5 per litre (Ministry of the Environment 2008), a value below those found in the waters of the Carapongo and Nievería reservoirs used for agricultural irrigation. It is understandable that these waters have somewhat higher levels of BOD through eutrophication during the period in which the water is retained, boosted by food remains and faeces from the farmed fish. This value, therefore, would not be a technical risk to health and the environment, since the organic matter present is used as a source of nutrients for the crops irrigated.

On the other hand, all the values determined for cadmium chromium, lead, arsenic and mercury are below those set by the ECAs, with the exception of lead in two water samples taken in the Ñaña and Carapongo irrigation channels, spot values that appear to occur temporarily and which may in all events indicate occasional mining or industrial discharges. We consider that, in general, these levels do not currently pose any risk to health or the environment.

Concentrations of faecal coliforms in the waters of the irrigation channels remain high, as has been found since 2006, values that in this 2013 evaluation reach 800,000 NMP/100 ml while the ECAs establish limits of 1,000 NMP/100 ml for watering short stalk crops such as vegetables. Fortunately, the results have also confirmed that the waters from the reservoirs built six years ago show acceptable values, between 7 and 17,000 CF/100 ml, except for one case of 33,000 in the Nievería reservoir that could be related to the tipping of sewage by inhabitants of neighbouring settlements or to retention periods shorter than those recommended.

Table 2: Results of the analysis of the health and environmental quality of water in Lima East agricultural areas

Code	Parameter	Sampling point	Sample	SS	BOD	Metals					Thermotolerant coliforms	Protozoa					Helminths			
						Cadmium	Chromium	Lead	Arsenic	Mercury		Blastocystis hominis	Endolimax nana	Entamoeba coli	Giardia lamblia	Iodamoeba butschlii	Ascaris lumbricoides	Hymenolepis nana	Strongyloides sp.	Uncinarias
	Unit			mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	µg/L	NMP/100 mL	org./L	org./L	org./L	org./L	org./L	org./L	org./L	org./L	org./L
	Place/item																			
NA	Union of Ñaña Peruvian University :																			
NA-A1	Irrigation channel water	Gatehouse 1 – main gate	M1	99	7.4	0.002	0.003	0.052	43.4	0.2	4.90E+05	5	8	20	15	0	3	0	1	0
			M2	15	5.1	<0.001	<0.002	0.009	17.3	0.1	3.30E+02	3	11	24	9	0	2	0	1	1
			M3	13	8.7	<0.001	<0.002	0.011	31.1	<0.1	1.30E+05	2	3	13	7	0	0	0	1	1
NA-A2	Reservoir water	Backpack irrigation, Mamani family	M1	21	5.9	<0.001	<0.002	0.01	32	0.1	1.70E+03	0	0	4	0	0	0	0	0	0
			M2	18	6.2	<0.001	<0.002	0.009	21.6	0.1	1.30E+01	0	1	2	0	0	0	0	0	0
			M3	19	3.9	<0.001	<0.002	0.009	20.9	<0.1	1.30E+03	0	1	2	1	0	0	0	0	0
CA	Agricultural plots in Carapongo:																			
CA-A1	Irrigation channel water	Raymundo Yaulis' plot	M1	32	2	0.001	<0.002	0.023	32.5	<0.1	3.30E+04	5	8	9	2	0	0	0	1	1
			M2	51	7.5	<0.001	<0.002	0.009	25.7	<0.1	7.00E+05	3	6	11	3	0	0	0	0	1
			M3	36	3	0.002	<0.002	0.093	37.4	0.2	7.00E+04	2	3	6	5	0	0	0	0	1
CA-A2	Reservoir water	Raymundo Yaulis' reservoir	M1	48	14.6	<0.001	<0.002	0.009	22.3	<0.1	2.20E+02	0	3	0	0	0	0	0	1	0
			M2	150	20.8	<0.001	<0.002	0.034	48	<0.1	6.80E+00	5	5	10	0	0	0	0	0	0
			M3	25	16	<0.001	<0.002	0.01	26.2	<0.1	4.60E+01	3	0	9	0	0	0	0	0	0
NI	Agricultural plots in Nievería:																			
NI-A1	Irrigation channel water	Mr Serna's plot	M1	18	11.8	<0.001	<0.002	0.012	24.9	<0.1	3.30E+05	9	15	30	11	0	1	1	2	1
			M2	33	13.8	<0.001	<0.002	0.01	25.5	<0.1	8.00E+05	2	8	20	7	0	1	0	0	2
NI-A2	Reservoir water	Mr Serna's reservoir	M1	66	22.6	<0.001	<0.002	<0.009	30.2	<0.1	1.30E+03	3	0	9	0	0	0	0	0	0
			M2	49	20	<0.001	<0.002	0.009	26.6	<0.1	7.90E+01	1	0	3	0	0	0	0	0	0
			M3	56	17.4	<0.001	<0.002	0.009	22.1	<0.1	3.30E+04	0	0	4	0	0	0	0	0	0
Environmental Water Quality Standards (Supreme Decree 002-2008-Ministry of Environment):																				
Category 3 – Irrigation of vegetables					15	0.005	0.1	0.05	50	1		0					<1			
		Tall stalk									2.00E+03									
		Short stalk									1.00E+03									

Source: PAHO 2014

Water in the irrigation channels maintains levels as high as 65 protozoa and five human parasite helminth eggs per litre of water. In the waters of the reservoirs, however, no helminths were found and protozoa were down to 20 per litre. It is likely that management of the reservoir facilitates allowing water to leave by overflowing, in which case the protozoa will leave the reservoir before dying. For this reason it is important to insist on the recommendation of not taking water from the reservoir by overflow, as these parasites float in water.

The vegetables evaluated show high levels of faecal coliforms, even when irrigated with reservoir water which, as shown in Table 2, is of higher quality, indicating the presence of other sources of contamination such as sewage from the neighbouring settlements, of which there are now more than in 2006. Similarly, all the vegetable samples show the presence of protozoa but not of helminths, indicating that the greatest risk to health is currently linked to these organisms. Although lettuce plants irrigated with reservoir water show a lower presence of parasitic protozoa than those irrigated with water taken straight from the channels, these crops do not achieve the minimum microbiological requirement for human consumption. Finally, none of the samples of fish from any reservoir exceeds the average limit of 500,000 CFU/g of aerobic mesophilic organisms, in addition to which levels of Staphylococcus aureus are below 100 CFU/g and there are no Salmonella spp. or human parasites, as required by the standard (SANIPES 2010).

Unlike the first evaluation, monitoring was able on this occasion to identify health risks in this agricultural area, and therefore a Sanitation Safety Plan (SSP) was prepared to control these risks, so that safe products could be placed on the market.

4. Conclusions and Lessons Learned

4.1. Conclusions

More than 97 per cent of samples of water from irrigation channels showed levels well above the maximum permitted levels of faecal coliforms. Between 17 and 31 per cent of samples of lettuce and radish irrigated with these waters were also above permitted limits.

The construction of small reservoirs was a viable option to reduce human parasites, such as protozoa and helminths, on condition that water from the channels was stored for about 10-14 days. This stored water and untreated river water were compared as sources of irrigation for vegetables, showing that the reservoir eliminates all parasites of human origin from the irrigation water and reduces faecal coliforms to less than 1,000 CFU/100ml. When radishes and lettuce were irrigated with reservoir water they had up to 97 per cent fewer faecal coliforms, a value well within permitted limits, while parasites were virtually absent from both these vegetables.

What is more, irrigation with reservoir water also had a beneficial effect on the growth rate and uniformity of the harvest, with a greater percentage of marketable products than when river water was used.

Since reservoirs occupy parts of productive land, it was proposed to compensate for this loss by fish farming, which would also provide a protein product to consume or sell. With 450 kg of fish food it is possible to produce 400 kg of Nile tilapia in a 500m^2 reservoir, with a productivity greater than 0.73 kg/m^2. The estimated cost was US$470 and sales income was US$880.

Monitoring conducted six years later confirmed that the use of reservoirs was still a viable tool to improve the quality of water that is contaminated when it comes from the river, for plant irrigation. Nevertheless, there are emerging issues such as human parasitic protozoa that must be removed, using techniques that need to be taught to the farmers.

4.2. Lessons Learned

The reservoir has proven to be an effective means of increasing income through the sale of good-quality vegetables and fish that improve human health and conserve the environment. These economic advantages are attractive to other farmers in the area, who have expressed an interest in the construction of reservoirs on their land in order to offer better quality products at a higher price.

Changes in land use that are occurring very rapidly in the area, especially the conversion of agricultural land into built-up areas, are a key factor that will influence acceptance of the use of reservoirs. Some landowners are already conducting subsistence farming, waiting for better prices to sell their properties. To motivate farmers to seek the production of healthy vegetables, it will be necessary to support the development of requirements and incentives through environmental regulations and improved market opportunities. It is hoped to continue working with local stakeholders and decision makers to raise the awareness of those responsible for the protection and management of water resources, for the production of safe food and for public health with a long-term perspective on sustainable development.

References

INEI. 2015. "*Perú: población total al 30 de junio, por grupos quinquenales de edad, según departamento, provincia y distrito*" (in Spanish). Lima, Peru: Instituto Nacional de Estadística e Informática. http://www.inei.gob.pe/estadisticas/indice-tematico/poblacion-y-vivienda/.

MINAM. 2008. "Environmental quality standards for natural water (ECAs)." Published by the Ministry of Environment through Supreme Decree 002-2008-MINAM, Lima, Peru.

Moscoso, J., H. Juarez, and T. Alfaro. 2007. "*Uso de reservorios para mejorar la calidad sanitaria del agua para el riego agrícola en el Cono Este de Lima*" (in Spanish). Lima, Peru: International Potato Centre (CIP)/CESAL, Urban Harvest Programme CESAL.

Moscoso, J., H. Juarez, and T. Alfaro. 2008. "*The Use of Reservoirs to Improve the Quality of Urban Irrigation Water.*" Urban Agriculture Magazine No. 20. The Netherlands: Resource Centre on Urban Agriculture and Food Security Foundation (RUAF).

WHO. 1989. "Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture." Geneva: World Health Organization.

PAHO. 2014. "*Plan de Seguridad en Saneamiento para el Estudio de Caso de la Zona agrícola del Cono Este de Lima, como parte del Proyecto Prueba del Manual de Planes de Seguridad de Saneamiento en Uso de Aguas Residuales en Lima, Perú*" (in Spanish). Lima, Peru: Pan American Health Organization.

SANIPES. 2010. "*Protocolo de calidad establecido en el Manual de Indicadores y criterios de Seguridad Alimentaria e Higiene para Alimentos y piensos de origen pesquero y acuícola aprobado el 2010, y que aplican para los productos hidrobiológicos crudos (frescos)*" (in Spanish). Lima, Peru: National Fish Health Service (Servicio Nacional de Sanidad Pesquera, SANIPES) of the Technological Institute of Production (Instituto Tecnológico de la Producción, ITP).

CASE 5

Water Reuse for Landscape Irrigation and Toilet Flushing in Brasilia, Brazil (Brazil)

M. R. Felizatto, F. C. Nery, A. S. Rodrigues, and C. M. Silva[1]

Abstract

The case presents the case of a water reuse project in Brasilia/ Brazil, assessing its operational results and economic outcomes. The water reuse experiment took place over 11 years (2000–2011) at the Wastewater Treatment Plant (WWTP) of the Sarah Hospital Rehabilitation Centre (CAGIF) on the shore of Lake Paranoa. The results achieved by CAGIF effluent concentrations were able to meet the more stringent standard for water reuse in landscaping irrigation and toilet flushing according to American and Brazilian guidelines, with the exception of the TSS variable, with average effluent concentration of 7 mg/L, 15 mg/L, 8 mg/L, 0.12 mg/L and 5.9 mg/L, for BOD5, COD, TSS, TP and TN, respectively. Regarding microbiological variables such as Total Coliforms and Faecal Coliforms, the final effluent results were always "not detectable". The economic outcomes demonstrate the feasibility of the project over a period of 20 years.

Keywords: water reuse, WWTP operating results, WWTP financial & economic analysis, Lake Paranoa, applications in Brazil

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1. Introduction

Sarah Hospital is a Brazilian reference in locomotor health. Its headquarters are located in Brasilia downtown, where there are no surrounding green areas that would enable the development of appropriate techniques for the treatment of people with severe physical incapacities. In the 1990s the situation worsened due to the significant increase in the number of patients with spinal cord injuries, caused mainly by traffic accidents.

As a solution, around 2000 CAGIF (Support Centre for the Great Physically Incapacitated) was implemented outside the central area of Brasilia. The building site, with an approximate area of 80,000 square meters, is located on the shore of Lake Paranoa, providing exceptional conditions for the implementation of this project. The facilities are near the lake, which provides conditions for water sports and others therapy, methods that have been successful in the treatment of incapacitated patients. The new facility operates separately from the headquarters, not requiring the same specialised technical services for diagnosis and treatment, such as operating rooms, X-rays or laboratories, which will remain centralised at the Sarah-Brasilia Hospital (Lima, 1996).

Lake Paranoa was created artificially in 1959 in order to increase moisture in the dry climate of Brazilian Central Plateau, to contribute to leisure activities, and to produce electricity. Over the years it has become a postcard for the federal capital. In the 1960s two wastewater treatment plants were built, North and South WWTPs (Wastewater Treatment Plants), treating the wastewater flow of a population equivalent to 225,000 inhabitants, while using the conventional activated sludge process (CAS). Accelerated urban occupation of the watershed and the inadequate treatment of wastewater contributed to the development of an eutrophication process in Lake Paranoa (Felizatto et al. 2000). In the 1980s a large proportion of algae showed that the lake was out of control, and the trophic state of the lake was considered eutrophic (CEPIS 1990).

An investment of three hundred million dollars was made to restore water quality, with the construction of two new advanced WWTPs for biological nutrient removal (Randall et al. 1992; van Haandel and Marais 1999; WRC 1984). The new South Brasilia WWTP has been in operation since 1993 and the new North Brasilia WWTP since 1994, with a wastewater treatment capacity equal to 1,000,000 inhabitants. Currently the two WWTPs treat 90% of the wastewater in the watershed. The decrease in the phosphorus load to the lake, or rather the removal of it, which is a limiting factor in the eutrophication of lakes, has been a success since the two new WWTPs began operating. The success of the 1990s Paranoa clean-up programme is a confirmation of the socio-cultural appreciation of the various recreational possibilities in the lake, once considered eutrophic and now heading for the mesotrophic state (Felizatto et al. 2000).

CAGIF WWTP was built in a place with no sewer pipe, due to the proposal of the Environmental Sanitary Company of Brasilia (CAESB). The idea was to implement Zero Effluent, which would treat all the wastewater. The recovered water would be used for landscape irrigation and toilet flushing.

This case presents the integrated design of wastewater management, treatment and water reuse utilised in the CAGIF, located in Brasilia, Federal District, Brazil.

In order to do that, it provides a detailed description of WWTP´s operational performance and the quality of the effluent produced, comparing these results with Brazilian and US standards for water reuse. The case also analyses the project from an economic and financial point of view, estimating the unitary costs of: construction and operation & maintenance (US$/m^3) and economic equivalence through following tools: Benefit-Cost Ratio (B/C), Payback, Net Present Worth (NPW), and Internal Rate of Return (IRR).

2. Materials and Methods

2.1. CAGIF WWTP

The process adopted by CAGIF WWTP is advanced wastewater treatment (WPCF 1989; Asano et al. 2007) combining a biological process with unit operations to produce an effluent useful for landscape irrigation (green areas) and toilet flushing.

The treatment plant was designed and built to operate for a population of 1,250 inhabitants – an average daily flow of 250 m^3/day. The unit is compact, built underground with reinforced concrete. Figure 1 shows the WWTP's flowsheet. CAGIF's WWTP is configured with the following units: (i) Biological Process Tertiary – a variation of CAS with the process for biological nitrogen and phosphorus removal reactor configured as a PHOREDOX process or Modified BARDENPHO® (WRC 1984; Randall et al. 1992); (ii) two Sedimentation Tanks with sludge return (underflow) for an Anaerobic Tank; (iii) Disinfection Tank - sodium hypochlorite solution; (iv) Coagulation with an aluminium sulphate solution; (v) Filtration - Sand Pressure Filter - operation in upflow and backwash by fluidisation; (vi) Adsorption – Granular Activated Carbon (GAC) Pressure Filter - operation in downflow and backwash by fluidisation, and (vii) Second Disinfection (in pipe). The Sludge Age was effected by removal of thickened sludge from secondary clarifiers (underflow) to the Aerobic Sludge Digester (Ae.S.D.) at regular intervals, and after 15 days of digestion the sludge is transported to the Brasilia North WWTP, where it is dewatered and the biosolids produced are finally disposed of.

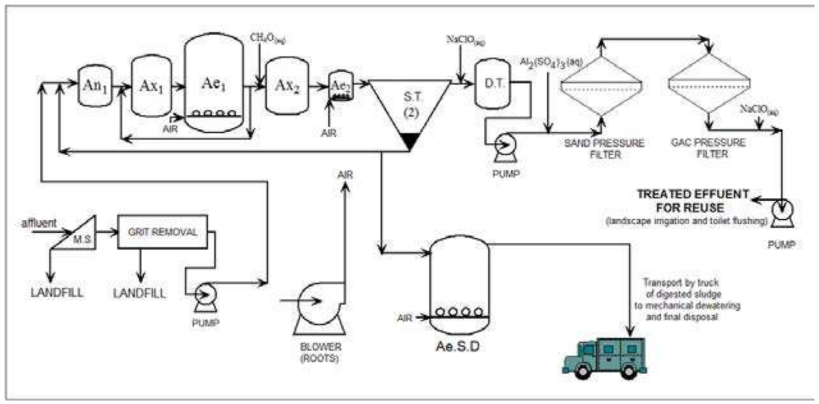

Figure 1: CAGIF WWTP Flowsheet (Felizatto 2001)
***Legend**: An1…Anaerobic Tank 1; Ax1…Anoxic Tank 1; Ax2…Anoxic Tank 2; Ae1…Aerobic Tank; Ae2…Aerobic Tank; S.T…Sedimentation Tank; D.T….Disinfection Tank, M.S…Manual Screen; Ae.S.D…Aerobic Sludge Digester.*

If the effluent is discharged into Lake Paranoa the concentrations of the treated effluent must not exceed the following values: (i) TSS = 10.0 mg/l; (ii) BOD5 = 10.0 mg/l; (iii) TKN = 4.0 mg/l; (iv) TP= 0.3 mg/l (v) Total Faecal Coliforms with removal of 99 to 100%, according to the recommendation of the CAESB. The quality of the final effluent was always based on the reference values recommended by CAESB, even without discharging the effluent into Lake Paranoa (Zero Effluent).

The collected samples were affluent, biological effluent (overflow from Sedimentation Tanks) and final effluent, and were collected as follows: once a week, sampled every two hours during a 24-hour period.

The chemical and microbiological variables monitored were: (i) Total Alkalinity; (ii) Anionic Surfactant; (iii) Organic Matter: Biochemical Oxygen Demand (BOD5), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS); (iv) Microbiology: Total Coliforms (TC) and Faecal Coliforms (FC) and (v) Nutrients: Nitrogen Ammonia (NH4+), Total Kjedähl Nitrogen (TKN), Nitrified Nitrogen (NOx), Total Phosphorus (TP) and Orthophosphate (PO4-2). Parasites (helminth eggs) were not monitored in the operation of the WWTP. All analyses were done by a laboratory hired by CAGIF.

As reported by Libânio et al. (2007), PRODES is a programme implemented by ANA in 2001 which applies a performance-based certification process in order to stimulate WWTP construction and its adequate operation. Data periodically demanded by PRODES include treated wastewater flowrates, influent organic loads and the removal efficiencies of key parameters (BOD, TSS, TN or TP and FC). In Brazil this programme is also known as the "treated wastewater purchase programme". It classifies WWTPs in nine categories ("A" through "I"), "A" being the less complex ones, listed in alphabetical order according to the plant's increase in complexity and its ability to remove organic matter, nutrients and coliforms (FC). Currently in Brazil it is very common to use the PRODES/ANA as a reference for WWTP performance and it classifies them in a scale of "A" to "I", "I" being the highest performance. The case aimed to classify CAGIF WWTP by PRODES/ ANA through the removal of values achieved by the treatment plant.

2.2. Water Reuse Standards

USEPA (2004) includes the following water reuse main types: (i) Urban, (ii) Industrial, (iii) Agricultural, (iv) Environmental and recreational, (v) Groundwater recharge and (vi) Augmentation of potable supplies.

Urban reuse systems provide reclaimed water for various non-potable purposes including: (i) Irrigation of public parks and recreation centres, athletic fields, school yards and playing fields, highway medians and shoulders, and landscaped areas surrounding public buildings and facilities; (ii) Irrigation of landscaped areas surrounding single-family and multi-family residences, general wash down, and other maintenance activities; (iii) Irrigation of landscaped areas surrounding commercial, office, and industrial developments; (iv) Irrigation of golf courses; (v) Commercial uses such as vehicle washing facilities, laundry facilities, window washing, and mixing water for pesticides, herbicides, and liquid fertilizers; (vi) Ornamental landscape uses and decorative water features, such as fountains, reflecting pools, and waterfalls; (vii) Dust control and concrete production for construction projects; (viii) Fire protection through reclaimed water fire hydrants, and (ix) Toilet and urinal flushing in commercial and industrial buildings (USEPA 2004).

In addition, reuse systems can supply major water-using industries or industrial complexes as well as a combination of residential, industrial, and commercial properties through "dual distribution systems". In "dual distribution systems", the reclaimed water is delivered to customers through a parallel network of distribution mains separate from the community's potable water distribution system. The reclaimed water distribution system becomes a third water utility, in addition to wastewater and potable water. Reclaimed water systems are operated, maintained, and managed in a manner similar to the potable water system (USEPA 2004). CAGIF has a "dual distribution system", especially for the use of water for toilet flushing, adding a separation mechanism of the two networks through a "cross-connection" device.

The development of planned water reuse projects in the United States began in the early twentieth century. California State was a pioneer in regulating recovery and water reuse. Its first enactment was in 1918. The first reuse systems were developed to provide water for irrigation in the states of Arizona and California in the late 1920s. In 1940 water reuse began as well as the use of chlorinated wastewater in steel mills. From 1960 onwards, urban public reuse systems have been developed in Colorado and Florida (Asano and Levine 1996).

In 1965, Israel's Ministry of Health issued regulations allowing the reuse of secondary effluent for irrigation of vegetable crops, excluding vegetables that are eaten raw.

In 1968, extensive research was conducted into direct potable reuse, which resulted in the implementation of the first and only Water Reclamation Plant located in Windhoek, Namibia: the Goreangab Water Reclamation Plant. This is the first case of direct potable reuse where the recovered water is used successfully for the drinking water supply of this municipality (Lahnsteiner and Lempert 2007). There was

a period during this experiment in which up to one third of the city's supply consisted of reclaimed water. It is currently operating at 26%, and may reach a maximum of 35% (Lahnsteiner and Lempert 2007; du Pisani 2005).

California has a long history of reusing and recovering wastewater. Its first regulation is from 1918. During all these years, there have been changes and the current guideline is shown in Table 1 (USEPA 2004; USEPA 2012).

Table 1: California Treatment and Quality Criteria for Water Reuse

Type of Use	Total Coliform Limits (MPN/100 mℓ)	Treatment Required
Fodder, Fibre, and Seed Crops Surface Irrigation of Orchards and Vineyards	-	Primary
Pasture for Milking Animals Landscape Impoundments Landscape Irrigation (Golf Courses, Cemeteries, etc.)	23	Oxidation and Disinfection
Surface Irrigation of Food Crops Restricted Recreational Impoundments	2.2	Oxidation and Disinfection
Spray Irrigation of Food Crops Landscape Irrigation (Parks, Playgrounds, etc.) Toilet and Urinol Flushing	2.2	Oxidation, Coagulation, Clarification, Filtration[a], and Disinfection

Legend: *[a] The turbidity of filtered effluent cannot exceed an average of 2 turbidity units during any 24 hour period.*

In Florida the "Reuse of Reclaimed Water and Land Applications" was adopted in 1989 and revised in 1990 by the Florida Department of Environmental Regulation. The standard of quality and treatment, including proposed revisions to the non-potable use of reclaimed water, are shown in Table 2 (USEPA 2004; USEPA 2012)

Table 2: Florida Treatment and Quality Criteria for Water Reuse

Type of Use	Water Quality Requirements	Treatment Required
Restricted Public Access Areas [a]	200 Faecal Coli MPN/100 mL 20 mg/L TSS 20 mg/L BOD_5	Secondary Disinfection
Public Access Areas [b] Food Crop Irrigation [c] Toilet Flushing [d] Fire Protection Aesthetic Purposes Dust Control	No detectable Faecal Coli MPN/100 mL 5 mg/L TSS 20 mg/L BOD_5	Secondary Disinfection and Filtration
Rapid Rate Land Application	200 faecal coli MPN/l00 mL 20 mg/L TSS 20 mg/L BOD_5 12 mg/L Total N	Secondary Disinfection

Legend:
[a] *Sod farms, forests, fodder crops, pasture land, or similar areas.*
[b] *Residential lawns, golf courses, cemeteries, parks, landscaped areas, highway medians, or similar areas.*
[c] *Only allowed if crops peeled, skinned, cooked, or thermally processed before consumption.*
[d] *Wot allowed where residents have access to plumbing system.*

USEPA, in partnership with USAID, published guidelines for water reuse in 1992, in order to serve as a guide for its various regional offices in some American cities and in states where there are no regulations yet. The USEPA set of instructions for the recovery and reuse of water covers various types of non-potable urban uses: industrial, agricultural and indirect potable reuse for groundwater recharge. It also raised the number of sources of surface water supplies. The USEPA criteria are shown in summary in Table 3 (USEPA 2004; USEPA 2012). It is important to mention that the microbiological indicator refers to Faecal Coliform and not to Total. Furthermore, there are no questions concerning virus control, just like the state of California.

No regulations have been implemented in the Brazil to date. However, Table 4 reports the values of Brazilian guidelines with regard to non-potable unrestricted urban reuse, which includes uses that are likely to be risky for the public and therefore require a higher treatment level. These reference values are from the National Water Agency (ANA 2005) and the Brazilian Association of Technical Standards (ABNT 1997).

Table 3: USEPA Treatment and Quality Criteria for Water Reuse

Type of Use	Water Quality Requirements	Treatment Required
Urban Reuse All types of landscape irrigati-on, (e.g., golf courses, parks, cemeteries) Vehicle Washing Toilet Flushing Use in fire protection systems and commercial air conditi-oners Other uses with similar access or exposure to the water	pH = 6 – 9 ≤ 10 mg/L BOD_5 ≤ 2 NTU No detectable Faecal Coli MPN/100 mL 1 mg/L Cl_2 residual (minimum)	Secondary Filtration Disinfection

Table 4: Brazilian Quality Criteria for Unrestricted Urban Non-Potable Water Reuse

Variable	ANA (2005)	ABNT(1997)
BOD5 (mg/ℓ)	≤ 10,0	-
TSS (mg/ℓ)	≤ 5,0	-
Turbidity (NTU)	≤ 2,0	< 5,0
Faecal Coliforms (MPN/100mℓ)	No detectable	< 200
Cl2 residual (mg/ℓ)	-	0,5 - 1,5

2.3. Economic and Financial Analysis

The "equivalence capital method" helps with decision-making where there are multiple alternatives that require a common measure of performance. Costs and benefits occur at different points in time and therefore have different values. Financial analysis methods are tools that will enable us to evaluate the aggregate of these costs and benefits using a common measure, such as follows: Net Present Worth (NPW), Net Future Worth (NFW), Benefit-Cost Ratio (B/C), Equivalent Uniform Annual Worth (EUAW), and Internal Rate of Return (IRR) (Ardalan 2000).

Net Present Worth (NPW) is the net difference of the present costs and benefits. Another method of assessing the viability of a system or comparing several systems is to calculate the net present value of the costs and benefits and obtain the benefit-cost ratio (B/C). If this ratio is greater than one, the project is profitable (Ardalan 2000).

A simple method for obtaining a quick evaluation of the alternatives is to calculate how long it takes to recover the initial investment. The time in any unit that it takes to recover the initial investment is called the Payback period. In this method, the net cash flow diagram is designed and then, by simple arithmetic calculation, the benefits and the cost are added year by year until the total equals the initial investment. It is obvious that the payback period neglects the time value of money. Moreover, it is only accurate when the interest rate is zero. Even with this shortcoming, many analysts consider this method to be a useful quick and easy means of comparison (Ardalan 2000).

Internal Rate of Return is a useful method for comparing the financial advantages of alternative systems, using a cash flow diagram. We calculate that specific rate of interest for the system that makes the net present value equal to zero. This rate is called the internal rate of return (IRR) and is denoted by i*. If this rate is higher than the minimum rate that satisfies the investor or the project manager, then the project is acceptable. This minimum rate is called the Minimum Acceptable Rate of Return (MARR). There is no mathematical formulae for calculating MARR. This has to be done by trial and error. Fortunately, there are computer programmes that easily make this calculation. Most of the spreadsheets on the market, such as Quattro Pro, Excel, etc., have provisions for calculating the IRR (Ardalan 2000).

3. Results and Discussion

3.1. Operating Performance Results

The data analysed were the last two years of operation at the CAGIF WWTP, 2010-2011, showing levels of removal of about 95% for the variables representing organic matter (BOD5, COD and TSS), and for the nutrients, nitrogen and phosphorus, 83% and 93%, respectively. As shown in Table 5, it also notes the removal capacity of 6.86 and 7.80 log units for Faecal Coliforms and Total Coliform, respectively.

Table 5: Performance by Total Removals from CAGIF WWTP (2010-2011)

Variable	Value (min.)	Value (max.)	Mean Value
BOD5	88.51	98.13	95.71
COD	87.64	97.76	95.21
TSS	90.00	98.64	95.52
TP	80.00	98.77	92.61
TN	28.36	94.59	83.19
TC	6.52	8.45	7.80
FC	6.32	7.52	6.86

Legend: *all removals expressed in %, except "log units" for TC and FC*

After interpreting the data shown in Table 5, CAGIF WWTP can then be classified as "I", the maximum level for a Brazilian WWTP plant configured as an advanced secondary treatment process followed by nutrient removal (phosphorus or nitrogen) and with disinfection at a minimum of 5 log units for the removal of faecal coliforms, with total removal rates of: BOD and TSS - 90%; TP - 85% or TKN - 80%. When the plant is ranked as "I" just one nutrient should be considered: TP or Total Kjedhäl Nitrogen (TKN). This category is commonly called Biological Nutrient Removal Plant (BNRP). The present study also included a COD total removal goal of 90%, the same value used for BOD_5 evaluation.

By analysing the standard values of effluent concentrations listed in Tables 2, 3, 4 and 5, it is evident that Brazilian standards of ANA are the most restrictive of the variables monitored: BOD5, TSS and Faecal Coliforms. The standard values proposed by ANA (2005) are part of the state of Florida compound with USEPA, always using the most restrictive values.

The results of the concentrations of monitored variables are shown in Table 6 for the final effluent from the WWTP CAGIF. Table 6 shows that BOD values are nearly always lower than what is recommended by the ANA (2005): 10 mg/L. While the variable TSS does not meet the recommended value (≤ 5 mg/L). Figure 2 shows the data of the concentrations of BOD5, COD, TSS and TN for the final effluent through the Box and Whisker plot, also known as the Box plot.

Table 6: Concentration of Final Effluent from CAGIF WWTP (2010-2011)

Variable	Value (min.)	Value (max.)	Mean Value
BOD5	3	12	7
COD	7	26	15
TSS	4	12	8
TP	0.05	0.32	0.12
TN	2.2	21.8	5.9
TKN	1.40	21.60	5.22
TC	-	-	Absence
FC	-	-	Absence

Legend: *all concentrations expressed in mg/L, except TC and FC (MPN/100mL)*

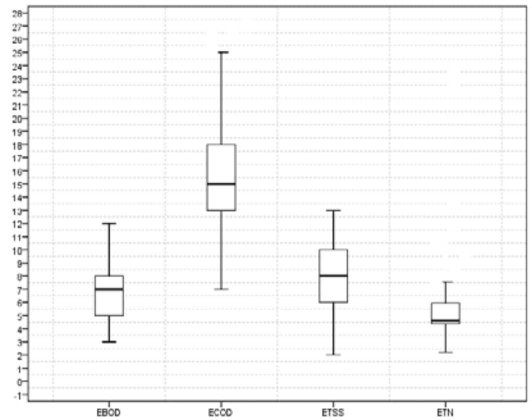

Figure 2: Box and Whisker plot of monitored final effluent variables: BOD_5*, COD, TSS and TN.*
Legend: *The letter "E" before the abbreviations of variables means that the data relate to the final effluent.*

The Box and Whisker plot in Figure 3 shows data for the total phosphorus concentration (TP expressed in mg/L) of WWTP CAGIF´s final effluent. It is observed in Figure 3 that almost all values are below 0.3 mg/L, the reference value recommended by CAESB if the effluent is discharged straight into Lake Paranoa. In 11 years of continuous operation the final effluent was never discharged into Lake Paranoa; all reclaimed water has always been reused in CAGIF for landscape irrigation and/or toilet flushing.

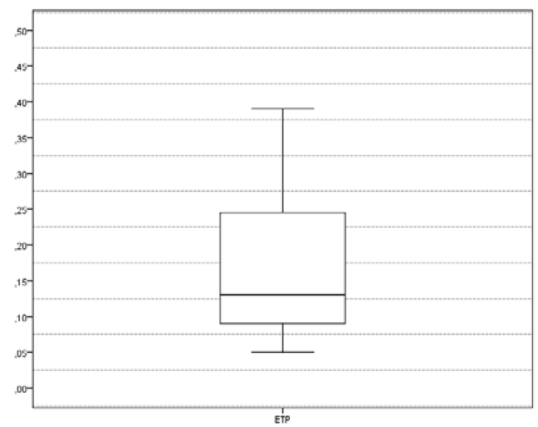

Figure 3: Box and Whisker plot for TP final effluent
Legend: *The letter "E" before the abbreviations of variables means that the data relate to the final effluent.*

3.2. Economic and Financial Analysis Results

Fernandes et al. (2006) reports the implementation costs and operating and maintenance costs for the CAGIF WWTP, showing also the economic and financial viability through the following tools: B/C ratio, Payback period, NPW and IRR. The base year used for calculations was 2004. The entire study was done using the Brazilian currency, the "Real" - R$. In this work the values in Brazilian currency were converted into US dollars, using as a conversion factor that was the average for 2004, i.e. US$ 1.00 to R$ 2.65.

The water balance for 2004 is illustrated in Figure 4, where observed. When the recovered water is reused for landscaping irrigation and toilet flushing, recycling is approximately 42%, which corresponds only to reuse in toilet flushing (Fernandes et al. 2006). When the reclaimed water is not reused in toilet flushing a new amount of water is supplied as potable water from CAESB, and in this situation the invoice result is the cost of drinking water consumption added to a wastewater cost of 100%, meaning that the expense with water is always double the value of potable water consumption. The treated average flow in the analysed period was 102 m^3/d corresponding to 41% of the design flow (250 m^3/d).

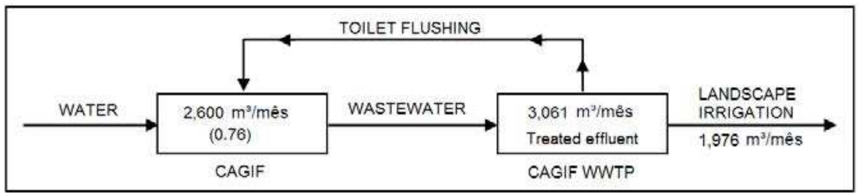

Figure 4: Block diagram of CAGIF´s water balance with water reuse in landscape irrigation and toilet flushing - base year 2004 (Fernandes et al. 2006)

Table 7 indicates the estimated values of CAGIF WWTP's construction, resulting in a unitary cost of US$ 157/inhab. or US$ 785/(m^3/d). The unitary cost per capita is more than US$ 91/inhab., being the highest value of a unit cost per capita of the 189 Brazilian WWTPs built over the years 2000-2001 (Nunes et al. 2005).

Table 7: Construction Cost of CAGIF WWTP[a]
(Base year 2004 – S$1.00=R$2.65)

Construction Stage	Cost (US$)
Civil Construction (earth-moving, masonry works, iron frame windows, shapes and waterproofing)	113,585.00
Equipment (blowers, centrifugal pumps, metering pumps, submersible pumps, sand pressure filter and activated carbon – GAC - pressure filter)	68,679.00
Hydraulic network (pipes, registers/valves, connections, etc.)	7,924.00
Architectural Design and Engineering, Supervision and technical responsibility	6,038.00
Overall	196,226.00

[a] *From: Fernandes et al. (2006)*

Table 8 describes the components of the operating costs of CAGIF WWTP for the year 2004, resulting in values of 73.4% and 26.6%, as fixed and variable costs, respectively. The resulting volumetric unitary cost of O&M is US$ 2.00/m^3, four to six times higher than the reported values for large WWTPs in the CAESB (2016) – US$ 0.30 to 0.50/m^3.

The high volumetric unitary cost is due to the scaling factor, and usually small WWTPs tend to operate with higher unit costs than larger ones. In addition, the unit cost is also influenced by the low capacity utilisation (41%) of the treatment plant and also because of the high fixed cost (73.4%).

The project's economic viabilities were calculated with a MARR of 10% and a period of 20 years, and the results are shown in Table 6. The CAGIF Water Reuse project can be considered viable in accordance with the methods used and the values shown in Table 9.

Table 8: Operation and Maintenance (O&M) Cost of CAGIF WWTP[a] (Base year 2004 – US$1.00=R$2.65)

DESCRIPTION	COSTS (US$)		
	Yearly	Monthly	%
1. Labor			**59.7**
1.1 Operator	31,000.00	2,583.33	(41.4)
1.2 Engineer Supervisor	13,735.00	1,144.58	(18.3)
2. Commodity (electricity)	5,790.00	482.50	**7.7**
3. Material			**4.9**
3.1 Aluminum Sulfate	168.00	14.00	(0.2)
3.2 Sodium hypochlorite	1,860.00	155.00	(2.5)
3.3 Filter media	1,620.00	135.00	(2.5)
4. Service			**20.0**
4.1 Laboratory analysis	10,236.00	853.00	(13.7)
4.2 Sludge Transport	3,168.00	264.00	(4.2)
4.3 Dewatering	1,584.00	132.00	(2.1)
5. Maintenance			**7.7**
5.1 Civil service	3,204.00	267.00	(4.3)
5.2 Equipment	2,532.00	211.00	(3.4)
Overall	74,897.00	6,241.42	**100**

[a] *From: Fernandes et al. (2006)*

Table 9: Results of Economic and Financial Analysis for Water Reuse in CAGIF Brasilia (Brazil). Period analysed: 20 years

Methods	Value
B/C	3.27
Payback	3 years and 4 months
NPW	US$ 445,483.00
IRR	30%

4. Conclusion

According to the analysis of the performance data for the CAGIF WWTP, it can be concluded that:

- The treatment plant is considered the most advanced process according to the Brazilian reference (PRODES/ANA). Organic matter removal is over 90% (BOD5, COD and TSS), total phosphorus up to 85%, TKN above 80%, and 5 logarithmic units for removing faecal coliforms;
- The quality of the final effluent did not meet TSS requirements, compared to the strictest guidelines for water reuse for landscape irrigation and toilet flushing. The data analysed by the study demonstrate that the biological removal of nutrients, coupled with coagulation, filtration and disinfection for wastewater treatment, cannot produce effluent with SST less than 5 mg/L. Nowadays it is common to use membrane separation processes (MSP) in Water Reclamation Plants to improve performance and produce recovered water with low values of TSS concentrations and turbidity. Ultrafiltration is the most used membrane separation process today; and
- The economic outcomes showed that WWTP was expensive to build, operate and maintain due to lower design flow and low capacity utilisation. However, the water reuse project CAGIF demonstrated economic and financial viability through the methods used in this study.

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References

Associação Brasileira De Normas Técnicas (ABNT). 1997. "*NBR 13969: Projeto, Construção e Operação de Unidades de Tratamento Complementar e Disposição Final dos Efluentes de Tanques Sépticos: procedimentos*" (in Portuguese).

Agência Nacional De Águas (ANA). 2005. "*Conservação e Reúso da Água em Edificações*" (in Portuguese). Brazil: Prol Editora Gráfica.

Ardalan, A. 2000. "Economic & Financial Analysis for Engineering & Project Management." Technomic Publication.

Asano, Takashi and Audrey D. Levine. 1996. "Wastewater Reclamation, Recycling and Reuse: Past, Present and Future." *Water Science & Technology* 33:10–11. doi:10.1016/0273-1223(96)00401-5.

Asano, Takashi, Franklin Burton, Harold L. Leverenz, Ryujiro Tsuchihashi, and George Tchobanoglous. 2007. *Water Reuse: Issues, Technologies, and Applications*. New York: McGraw-Hill.

CAESB. "*Intranet CAESB - Custos Operacionais da ETEs da POE*" (in Portuguese), Accessed January 27, 2016. http://www.caesb.gov.br.

CEPIS. 1990. "*Metodologias Simplificadas para la evaluacion de Eutroficacion en Lagos Calidos Tropicales*" (in Spanish). Regional Programme CEPIS/HPE/OPS.

Felizatto, M.R., Itonaga, L.C.H., Gobatto Cavalcanti, C. and Teixeira Pinto, M.A. 2000. "Statistical tendency analysis of Lake Paranoa limnological data (1992-1999) and its trophic state classification based on CEPIS methodology." Proceedings of SIDISA 2000: International Symposium on Sanitary and Environmental Engineering, Trento, Italy.

Felizatto, M.R. 2001. "*ETE CAGIF: Projeto Integrado de Tratamento Avançado e Reúso Direto de Águas Residuárias*" (in Portuguese). 21o Congresso Brasileiro de Engenharia Sanitária e Ambiental, Anais, João Pessoa, Brazil.

Fernandes, G. T., Felizatto, M. R., and Souza, M. A. A. 2006. "*Análise Econômica de Projeto Integrado de Tratamento e Reúso de Água – O caso da ETE CINR (Brasília-DF)*" (in Portuguese). VIII Simpósio Ítalo Brasileiro de Engenharia Sanitária e Ambiental, Anais.

Lahnsteiner, J. and Lempert, G. 2007. "Water management in Windhoek, Namibia." Water Science & Technology 55:1–2.

Libânio, P.A.C., Nunes, C.M., de Oliveira, E.F.C.C., Soares, S.R.A., Brito, M.C.S.O.M. 2007. "*Implantação e Operação de Estações de Tratamento de Esgotos; Experiências no Âmbito do Programa Despoluição de Bacias Hidrográficas (PRODES)*" (in Portuguese). 24° Congresso Brasileiro de Engenharia Sanitária e Ambiental, Anais, Belo Horizonte, Brazil.

Lima, J.F. 1996. "*Centro de Apoio ao Grande Incapacitado Físico – Ante Projeto*" (in Portuguese). Associação das Pioneiras Sociais (APS).

Nunes, C. M., Libânio, P. A. C., Ayrimoraes, S. R. 2005. "*Custos Unitários de Implantação de Estações de Tratamento de Esgotos a partir da base de dados do Programa de Despoluição de Bacias Hidrográficas – PRODES*" (in Portuguese). 23° Congresso Brasileiro de Engenharia Sanitária e Ambiental, Anais, Campo Grande, Brazil.

du Pisani, P.L. 2005. "Direct Reclamation of Potable Water at Windhoek's Goreangab Reclamation Plant." In *Integrated Concepts in Water Recycling*, edited by S.J. Khan, A.I. Schäfer, M.H. Muston.

Randall, Clifford W., James L. Barnard, and H. David Stensel. 1992. "Design and Retrofit of Wastewater Treatment Plants for Biological Nutrient Removal." In *Water Quality Management Library Volume 5*. Technomic Publication.

U.S. Environmental Protection Agency (USEPA). 2004. "Guidelines for Water Reuse." Washington D.C.: Municipal Support Division Office of Wastewater Management Office of Water.

U.S. Environmental Protection Agency (USEPA). 2012. "Guidelines for Water Reuse." Washington D.C.: Municipal Support Division Office of Wastewater Management Office of Water.

van Haandel, and A. e Marais, G. 1999. "*O Comportamento do Sistema de Lodo Ativado - Teoria e Aplicações para Projetos e Operação*" (in Portuguese). Campina Grande, Brazil: Publisher of the Federal University of Paraíba.

WPCF. 1989. "Water Reuse – Manual of Practice" (Second Edition). Alexandria, VA: Water Pollution Control Federation.

WRC. 1984. "Theory, design and operation of nutrient removal activated sludge processes." Pretoria, South Africa: Water Research Commission.

SECTION II:

HEALTH & ENVIRONMENTAL ASPECTS

CASE 6

Good Irrigation Practices in the Wastewater Irrigated Area of Ouardanine, Tunisia (Tunisia)

Olfa Mahjoub[1], Mohamed Mekada[2], and Najet Gharbi[3]

Abstract

The reuse of treated wastewater (TWW) for irrigation in the Ouardanine area dates back to the 1990s. In the early 2000s, farmers have claimed for the installation of a filtration device at the treatment plant outlet to remove suspended solids. Later, the government constructed a storage basin and installed a battery of filters upstream of the irrigated area. In open fields, the surface irrigation of fruit trees was replaced by drip irrigation to decrease water consumption, on the one hand, and to reduce contact between practitioners, soil, and fruits with TWW, on the other hand. Restricted irrigation is fully respected by growing only crops that are allowed by the regulation, such as fodders and fruit trees. In order to benefit from the nutrients available in TWW, a nursery was established for the production of various kinds of plants that represent a valuable economic benefit. Despite the substantial progress, farmers are unable to value the nutrient load brought by TWW yet. As for the health aspects, vaccination is assured regularly neither by the public health services nor by farmers themselves; the latter state that they have mastered the situation with no accidental contamination reported.

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The cessation of irrigation before harvesting is difficult to respect since peach fruits are highly demanding of water in the late growing season. Consequently, an appropriate post-harvest handling of fruits is assured to protect consumers. The role of the extension services is also sought to be more efficient.

Keywords: Good irrigation practices, biosolids, filtration, crop restriction

1. Introduction

Conventional water resources are becoming increasingly scarce. Climate change and pollution caused by anthropogenic activities have considerably reduced the available quantity of water. Under such circumstances, arid and semi-arid countries have to rely on non-conventional water resources as a potential source to irrigate crops. Wastewater is regarded worldwide as an alternative resource. Handling of this resource remains delicate and prone to failure. It requires the application of specific practices, especially when treatment is lacking or is inefficient in reducing the load of pollution to an acceptable level that guarantees safe reuse.

Farm-based measures can play an important role in reducing the risks related to wastewater reuse, especially in countries where treatment is rather decentralised or with low efficiency. The participation of the public in the reuse of treated wastewater (TWW) with end-users is regarded as a good practice because it may help to provide better service (Keraita et al. 2010). Other aspects can also be features of good practices such as the role played by institutions and the enforcement of regulations, when they exist.

Tunisia initiated the experience of reusing TWW for the irrigation of citrus orchards in La Soukra, in the north-east of the country in early 1960s. In the 1980s, research outcomes have shown the likelihood of contaminating soils and crops after the reuse of TWW. National regulations calling for restrictive reuse were established in 1989 inspired by both World Health Organization (WHO) and Food and Agriculture Organization (FAO) guidelines. Chemical and biological contaminants were limited to guarantee safe reuse (Guardiola-Claramonte et al. 2012). The specifications set by the law in 1995 required the implementation of good practices to protect the health of practitioners such as farmers and workers in the field. To date, no official guidelines for good practices have been published.

In Tunisia, the effluents of 26 out of the 110 existing wastewater treatment plants (WWTP) are used for the irrigation of agricultural lands. About 28 irrigated schemes exist currently and only 17 are actually in operation. The average rate of intensification is around 46% for the last 10 years (DGGREE 2014). Hence, few irrigated areas are attempting to fulfil the requirements for safe reuse in agriculture. One of the most thriving irrigated areas is located in the Ouardanine region where the landscape has been transformed over 18 years thanks to the reuse of TWW. TWW in Ouardanine has been identified as the only alternative water resource in the region, constraining the population in adjusting to the prevailing conditions to guarantee their food security. The area of Ouardanine is considered a success story in terms of wastewater reuse in Tunisia. Nevertheless, very few or no publications have introduced the case study to the large research and development (R&D) communities to showcase the successes and opportunities of improvements.

The general objective of this case is to highlight the good practices behind the success of reusing TWW in agriculture in the irrigated area of Ouardanine. The focus will be on the case study of a farmer cultivating peaches for more than 15 years. Lessons learned and potential improvements will be highlighted as well. This case is based on a literature review and an interview with a farmer (President of the Agricultural Development Group) and stakeholders, in addition to field observations.

2. General Context and Background

The district of Ouardanine is located 130 km from the capital, Tunis. It is in the Governorate of Monastir, in the eastern central part of Tunisia (Figure 1). The region is a semi-arid climate and therefore experiences a water deficit estimated at 1,000 mm/y. The Sahline-Ouardadine aquifer underneath the region is saline (4.3 g/L) and overexploited (110%) (CNEA 2008), and it is therefore no longer used for irrigation. Besides, water from the Nebhana dam used exclusively for the irrigation of farmland in central Tunisia is not available for the region of Ouardanine.

Agricultural activity in the region is based on dry farming. Ninety-seven per cent of orchards contained olive trees irrigated using the system of meskat, the traditional rainwater harvesting system. The reuse of wastewater is deemed to be the only alternative water resource to support intensive irrigated agriculture (Vally Puddu 2003), especially in the region of Ouardanine.

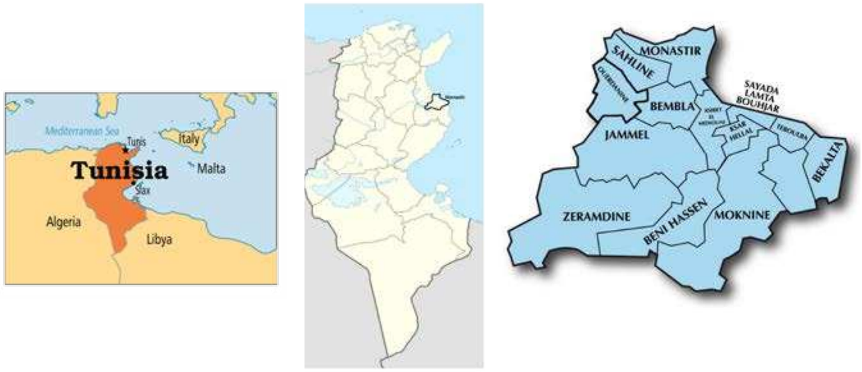

Figure 1: Location of Tunisia, Monastir governorate, and district of Ouardanine

From an environmental standpoint, Ouardanine has long experienced the impacts of discharging untreated sewage into the Oued Guelta stream, which resulted in the degradation of the rural area (Hydro-plante, 2002). Under pressing demand from farmers, the National Sanitation Utility (ONAS), as the producer of TWW in Tunisia, started reclaiming effluents in the wastewater treatment plant (WWTP) of Ouardanine. Based on the farmers' request, the Ministry of Agriculture and Water Resources subcontracted a study for planning the irrigation of 50 ha of agricultural land for a group of 40 farmers (CRDA 2015).

The irrigated area of Ouardanine was established in 1994 and irrigation started in 1997. Currently, the irrigated area stretches over about 75 ha. Crops irrigated with secondary effluents consist mainly of fruit trees comprising about 34 ha of peaches, pomegranates, figs, apples, and medlars. Forage crops like alfalfa and barley are grown as well (CRDA 2015).

At the installation time, the area of Ouardanine used to consume 40% of the TWW produced (about 4,000 m^3). Now it consumes about 140,000 m^3 of water/year (2014-2015). Water management is attributed to the Agricultural Development Association (GDA) (DGGREE 2015).

3. The Wastewater Treatment Plant of Ouardanine

The WWTP Ouardanine was built in 1993. It collected the effluents of 17,000 citizens and has a capacity of treatment of 1,000 m^3/d (Figures 2 and 3). It operates with an oxidation pond treatment system. The WWTP treats 882 m^3/d in summer with a maximum capacity of 1,010 m^3/d (DGGREE 2015). Currently, the population of Ouardanine counts 21,814 inhabitants corresponding to about 6,312 households (National Institute of Statistics 2015), which explains its forthcoming rehabilitation in the year 2016.

Figure 2: WWTP Ouardanine (Google Earth 2015)

Figure 3: Secondary clarifier at the WWTP Ouardanine (with permission of O. Mahjoub 2015)

The WWTP is located in the area of Oued El Guelta, close to the irrigated area, which is an advantage in itself. Indeed, one of the identified barriers to the development of reuse in Tunisia is the remoteness of agricultural lands from the WWTPs (DGGREE 2014). Wastewater is chiefly of domestic origin with a few industries (slaughterhouse, perfume industry, olive mills, car washing stations, etc.) that have caused cases of failure at the treatment plant, followed by a drop in the quality of the TWW delivered for irrigation (DGGREE 2015).

The WWTP of Ouardanine produces about 350 m^3/d of wet sewage sludge, which is usually spread on drying beds (Figure 4). The use of biosolids in agriculture is not allowed officially even though National Standards were well established in 2002 (NT 106.20 (2002)). Spreading biosolids on agricultural soils is on-going at a pilot scale.

Figure 4: Sewage sludge on drying beds at the WWTP of Ouardanine (with permission of O. Mahjoub 2015)

The management of biosolids is an important issue for the environment since its usage as a fertiliser for agricultural lands is not allowed on a large scale yet. Alternatively, the produced volume of biosolids is released into the Oued El Guelta stream (Figure 5) and the area surrounding the WWTP, thus causing drainage problems. A raise in the water table level in the years 2002-2004 (Vally Puddu 2003) has resulted in the complete perishing of fruit trees. Dredging of the stream is planned during the coming years.

Figure 5: Discharge of raw and treated effluents and sewage sludge in the Oued El Guelta stream (with permission of O. Mahjoub 2015)

4. Good Practices for Reuse in Agriculture

The WHO Guidelines published in 2006 were established for health protection purposes, by offering several measures and concepts (WHO 2006). In Tunisia, these guidelines have still not been translated by water managers and extension services into simple and practical actions to be implemented on the field. WHO Guidelines related to the reuse of TWW in agriculture consider that good irrigation practices depend on water quantity, water quality, soil characteristics, crops selection, irrigation techniques, leaching, and management practices (WHO 2006). These aspects will be considered below for describing good practices applied in the irrigated area of Ouardanine.

4.1. Quality of Treated Wastewater

Water resource quality defines subsequent uses and inherent risks. Considering the types of reuse of TWW applied in developing countries, it is recommended that the quantity and quality be analysed against potential reuse applications and quality requirements (UNEP 2005) in order to guarantee acceptability by end-users, on the one hand, and to mitigate the risks to practitioners and the environment, on the other hand.

In Tunisia, WWTPs existed before the establishment of the irrigated areas. Consequently, the quality of TWW supplied for the irrigation of crops may or may not satisfy the quality requirement for reuse downstream, entailing various risks to end-users and consumers, if it is not well managed. Improving TWW quality after conventional secondary treatment can be achieved through several options known as "non-treatment", generally applied in countries where treatment is not available (WHO 2006).

The WWTP of Ouardanine produces a secondary biologically treated effluent that is allowed to be used exclusively for restricted irrigation based on the Water Code, related decrees, and the National Standards. Quality monitoring of the TWW in Ouardanine during the course of the research programme and by regional authorities showed that salinity is moderate (1.7–1.9 g/L), implying slight to moderate restriction for irrigation (Ayers and Westcot 1985). Chemical and biological parameters are almost all within the Tunisian Standards of Reuse except for an excess in total suspended solids (41.7 mg/L vs 30 mg/L) and Chemical Oxygen Demand (92 mg O_2/L vs. 90 mg/L) (Bahri and Mahjoub, 2007; CRDA 2015). However, the COD value that considerably exceeded the threshold was measured in 2014 (DGGREE 2014). Besides, CRDA reported high values of suspended solids (CRDA 2015). Oil mills and slaughterhouses discharging effluents in the sewer system may also cause troubleshooting of the treatment process and lower the quality of TWW (presence of feathers, oily substances, etc.). The concentrations of heavy metals in TWW are below the threshold values fixed by the National Standards of Reuse (Bahri and Mahjoub, 2007; DGGREE 2015). Some elements may occasionally register high concentrations, like Chromium (Cr) detected at up to 7.3 mg/L in 2003, probably caused by discharge by textile industries. High concentrations of Cr, up to 76 mg/kg dry matter, were found in soils fertilized with biosolids, compared to values recommended by the EU Commission (60 mg/kg dry matter) (Berglund and Claesson 2010).

It is clear that the WWTP does not seem to be as efficient as thought in providing a TWW quality that meets standards and farmers' expectations. TWW needs further improvements to be suitable for irrigation. To achieve this, a filtering station and storage basin were installed and are described below.

4.2. Storage Reservoir

The installation of a reservoir downstream from the WWTP for collecting effluents offers the possibility of storing the water for periods of the year where effluents are not available to meet the crops' water requirements. In addition, it has the advantage of being an additional treatment that is very likely to improve TWW quality by reducing the pathogen load (Jiménez et al. 2010).

In Ouardanine, a storage basin with a capacity of 500 m^3 was installed upstream, about 5 m high, to guarantee gravity distribution of TWW to the irrigated area. The low quality of TWW transferred into the basin used to result in the settling of sludge and clogging of the irrigation systems. Basin dredging used to be problematic, resulting in environmental nuisance.

In 2007 a storage basin of 1,000 m^3 was constructed by the CRDA with the aim of regulating the amount of TWW distributed to the irrigated area and of adapting it to crop requirements (Figure 6). This basin was also meant to improve the quality of the TWW by allowing the settlement of suspended solids and the die-off of microorganisms. Maintenance and cleaning of the basin and of the pumping station are assured by CRDA workers once a year (CRDA 2015).

Figure 6: Storage basin of 1,000 m^3 and maintenance of the pumping station in Ouardanine (with permission of O. Mahjoub 2015)

4.3. Filtration

The filtration of secondary biological effluents is recognised to allow the removal of residual particulate matter and pathogens, such as helminth eggs and protozoan cysts (Jiménez 2007). Various types of filtration can be adopted to remove about 1 log unit of pathogenic bacteria and viruses.

In Ouardanine, effluents at the outlet of the WWTP have always shown floating suspended solids that escape the settling tank. The farmers suffered the presence of this material that caused clogging of the drippers. As a result, some of them have abandoned drip irrigation or have removed the nozzles. Consequently, the initial pathogen reduction target was not achieved and water saving was disrupted because of the larger amount of water delivered to plants.

To reduce the load of suspended particles, a net was placed at the outlet to perform gross filtration (Figure 7). WWTP workers are charged for the replacement and maintenance of this device. This system has been installed since 2003. Currently, the net is replaced by a removable sieve doubled with a metallic net installed in 2004 (Figure 7).

To further improve the quality of TWW, a battery of filters comprising a granular filter, sand filter, and sieve filter was installed by CRDA at the outlet of the storage basin (Figure 8). In order to avoid failure of the filtration system, material used for filtration (sand) should be changed regularly, every three years. Contamination with helminth eggs occurred during the course of the growing season in 2015 and has caused the interruption of the irrigation water supply for 25 days, which has significantly affected the irrigation schedule. This shows that filtration should not be considered a treatment process in itself and should be accompanied by an efficient treatment process in WWTP upstream. In the case of a similar incident, farmers would claim alternative solutions for the storage of larger volumes in such a way that the yield and quality of the crops are not affected.

The installation of a lower porosity filter, though delivering 50% of the initial flow, was suggested by the farmer to reduce the risk of the passage of pathogens. The President of the GDA was willing to adapt his irrigation schedule to this new filtration system by setting priorities based on the type of crops and plants to be irrigated: pomegranate, seedlings, and young plantations in the nursery.

Figure 7: Net installed at the outlet of the WWTP in Ouardanine in 2003 (left) and the new sieve and net installed in 2004 (right) (with permission of O. Mahjoub, 2003, 2015)

Figure 8: Battery of filters at the outlet of the storage basin (with permission of O. Mahjoub 2015)

4.4. Crop Restriction in Reuse

Crop restriction is one of the health protection measures to be applied on farms to reduce the risk of contamination for exposed consumers, especially for crops eaten raw (WHO 2006). In Tunisia, the decision of the Minister of Agriculture in 1994 clearly mentions the crops allowed to be irrigated with TWW. These are mainly fruits trees, cereals, fodders, and industrial crops.

The crops grown in Ouardanine used to be olive trees exclusively. The introduction of TWW in the region resulted in a significant modification of the cropping pattern and socio-economic situation. The crops cultivated currently are cereals (barley: 2 ha), fodder crops (alfalfa: 1 ha), olive trees (olives: 6 ha of table olives and 15 ha of oil olives), and fruit trees (34 ha) (CRDA 2015). The latter are mostly peaches and others fruits such as pomegranate, figs, and apples.

The farmer we interviewed is the President of the GDA. He has a cultivated area of 6 ha composed of: 1 ha of barley and 1 ha of alfalfa irrigated by improved furrow irrigation, 2 ha of pomegranate and 2 ha of peaches (Figure 9). In winter time, only forage is irrigated while in summer the volume of TWW produced seems to be sufficient to irrigate the whole area, provided no interruption occurs.

Figure 9: Peach trees irrigated in the area of Ouardanine in winter (left) and summer (right) (with permission of O. Mahjoub 2015)

In Tunisia, the irrigation of industrial crops with TWW is allowed by regulation. Pelargonium graveolens, more commonly called geranium, is a shrub grown as an inter-row crop between pomegranate trees (Figure 10). Pelargonium is grown in the TWW irrigated area of Ouardanine. This plant is grown for its foliage and flowers, which are used for distillation and the production of scent. Distillates and essential oils are also produced for curative and culinary features. To comply with safe TWW reuse rules, the farmer is using drip irrigation to avoid contamination of the foliage. He stated that he sells it in bunches at the local market and praised the high economic value. Yet some microbiological analysis should be made to assure the innocuousness of the foliage from bacterial contamination.

Figure 10: Pelargonium graveolens grown as inter-row crops with pomegranate (with permission of O. Mahjoub 2015)

Besides pelargonium plants, cut roses are grown in greenhouses irrigated using drip irrigation. Roses, olive trees, and other plants are also produced in nursery (Figures 11 and 12).

Figure 11: Cut roses cultivated in greenhouses and irrigated with TWW using drip irrigation (with permission of O. Mahjoub 2015)

Figure 12: Plants in the nursery irrigated with TWW (including olives, apples, roses, etc.) (with permission of O. Mahjoub 2015)

4.5. Irrigation Methods and Scheduling

Irrigation methods are regarded as an efficient way to prevent the chemical and biological contamination of soil, crops and end-users and a health protection measure. WHO classified irrigation methods as "non-treatment" options (WHO 2006).

In Ouardanine, an irrigation network installed for the area is 2.3 km long. The area is equipped with valves and irrigation equipment. Cereal and fodder crops are irrigated with an improved surface method. During the course of more than 15 years, the interviewed farmer has adopted various irrigation systems, including most recently an integrated dripper delivering 4L/hr. The farmer thinks it is very important to give the appropriate amount of water to trees to guarantee the good quality and yield of peaches.

Farmers keen to adopt water-saving techniques are encouraged by the government with incentives. Up to 60% of the investment cost of the irrigation system can by subsidised when switching from traditional irrigation techniques like furrow irrigation to more water-saving methods like sprinklers or drip irrigation.

4.6. Water Allocation

The GDA of Ouardanine is in charge of irrigation water management in the irrigated area. It also sells the water and maintains the infrastructure for the existing 36 farmers. The distributed amount of water is allocated according to land size, the number of trees and their age. In the case of a water shortage, young plantations and nurseries are supplied as a priority. Nevertheless, water needs may be exceeded, especially before the harvesting period, because farmers think that the fruits are more water demanding (CRDA 2015).

5. Use of Biosolids in Agriculture

Opportunities to use biosolids in agriculture in Tunisia were assessed in the late 1980s and their use as a fertiliser in agriculture was practiced in the 1990s (Bahri and Houmane, 1987; Bahri, 1995). Due to health concerns, the use of biosolids in agriculture was interrupted in 1998 by the Ministry of Public Health until the National Standards were established in 2002. Since that time, the discharge of biosolids has become a challenging environmental issue. The lack of follow-up and/or enforcement for use has resulted in the accumulation of sludge in areas surrounding WWTPs. Currently, the application of biosolids on agricultural land is limited to experimental plots conducted as demonstration pilot projects.

The area of Ouardanine has a sandy clay silt, sandy silt clay or sandy clay soil. The farmer estimates that soil is poor requiring organic amendment for improving its fertility. The high price of manure made of biosolids is a good alternative to organic fertilisers. In Ouardanine, biosolids have been used as fertiliser since 2009 to rehabilitate the subsoil. An area of 1 ha is currently amended under the regular monitoring of the Ministry of Agriculture as one of the demonstration projects. The use of biosolids is carried out according the National Standards. The estimated amount of 6 T/ha is expected to be spread over 5 years.

The farmer remains curious about the joint effect of applying TWW and biosolids in terms of the amount of fertilisers and impacts on soil, yield and fruit quality.

6. Potential Areas of Improvement

6.1. Nutrient Recycling/Recovery

Fertilisers are becoming increasingly expensive, thus entailing high production costs. Wastewater reuse has the advantage of providing a considerable amount of nutrients that were used for a long time in developing countries worldwide.

In Ouardanine, farmers are irrigating with TWW and delivering water doses based only on the crops' water needs, while ignoring the fertilizing load. In doing so, they are not benefitting from nutrients brought by TWW. Usually, phosphorus is present at low concentrations, requiring additional mineral fertilization. Whilst nitrogen is present at such high concentrations, groundwater may be contaminated if TWW is not well managed. To date, farmers in Ouardanine have neither the clues nor tools to evaluate the amount of fertilisers present in TWW. Therefore, more guidance is needed in this respect.

6.2. Monitoring of TWW Quality

Based on national regulations, regular monitoring of the quality of TWW used for irrigation and soil should be performed more frequently to guarantee the safer reuse of TWW.

6.3. Irrigation Scheduling

The farmer may be still overestimate the water needs of crops in order to guarantee a good quality and yield. More research has to be conducted to optimize the use of TWW in terms of water, fertilisers, and salt build-up.

6.4. Health Protection and Medical Control

Vaccination is preventive measure that mitigates the risk of contamination with pathogens. In Ouardanine, farmers' comments and records of the growing season in 2014/2015 (DGGREE 2015) revealed that there is neither health control nor vaccination for employees of the Regional Department for Agricultural Development (CRDA Ouardanine) or for farmers at the Farmer's Association. Farmers declared that no major incidents due to microbiological contamination occurred in the past.

The health control of farmers is under the responsibility of the Department of Hygiene, Milieu and Environmental Protection (DHMPE) under the Ministry of Public Health, which is in charge of the microbiological quality control of the effluents, including crops. Vaccination was shown not to be regularly performed in the area to prevent potential microbiological pathogen-related diseases. Farmers confirmed that no health issues occurred in the area thanks to all the other preventive measures.

6.5. Cessation of Irrigation before Harvesting

The cessation of irrigation can reduce the load of pathogens that may potentially be transferred to the soil and to the irrigated produce by contributing to the die-off of bacteria and viruses.

According to the Tunisian Standards of Reuse and related specifications, farmers should cease irrigation two weeks prior to harvesting fruits or crops. Based on comments by farmer, the delay between irrigation and harvesting can be respected neither for forage nor for peaches. For forage harvested for grazing, it has been shown that 99% of viruses can be eliminated after two days of exposure to sunlight (Feigin et al. 1991) which could prevent the contamination of animals. For peaches, meanwhile, it is important for the farmer to irrigate intensively during the late period of the growing season for better fruit quality and yield; therefore irrigation does not seem to be stopped. This may entail higher water consumption and health risks. Better guidance should be provided to farmers on this aspect.

6.6. Role of the Extension Service

The extension service does not seem to provide sufficient outreach to the farmers in the region. Improvements observed in the area are said to be the results of the farmers' own initiatives. The role of the extension service should be enhanced for safer irrigation. More trust should be established in the relationship between farmers and local stakeholders.

6.7. Fruit Commercialisation

Fruits produced in Ouardanine are sold at local and regional markets with no distinction from fruits irrigated with conventional water. However, local consumers seem to recognise peaches irrigated with TWW from Ouardanine. The reluctance of some consumers towards fruits irrigated with TWW, expressed as a "yuck factor", should be resolved by raising awareness and enforcing good practices in the field when harvesting, packaging, etc. Stakeholders speak about establishing a system of traceability for products to guarantee their safety, on the one hand, and to protect the health of customers, on the other hand.

7. Conclusions and Recommendations

The area of Ouardanine irrigated with TWW is considered a successful case study in Tunisia. The application of good practices for safe reuse in agriculture is behind this achievement. The reuse of TWW in this area has brought a number of benefits to the rural population and to the region as a whole at various levels (environmental, economic, health, etc.). This has limited the discharge of raw wastewater into water bodies and protected natural resources. It was also beneficial to the development of economic activity that improved the quality of life of the population and contributed to the prosperity of the region. Applying good practices for TWW reuse in the region of Ouardanine was an asset. Nevertheless, a number of improvements are sought for the development of agricultural activity while taking into account the various impacts of the project.

The President of the GDA, as a representative of the farmers' community in the region, is looking for more outreach and is recommending several actions including but not limited to the following:

- Introduction of a subsurface irrigation system for unrestricted irrigation to evolve toward more permissive regulations and a larger range of crops.
- Establishment of an agreement between all the stakeholders at the local level (TWW producer, manager, and end-user) to guarantee the continuous TWW supply during the irrigation period and prevent any variation that may affect production.
- Optimisation of irrigation and fertilization of crops, and development of indicators for water efficiency, nutrients and water consumption with regard to the quality of TWW, biosolids, and soil.

8. Acknowledgments

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References

Ayers, R. S. and D. W. Westcot. 1985. "Water Quality for Agriculture." *FAO Irrigation and Drainage Paper* 29:174 Rev. 1, Rome.

Bahri, A. and B. Houmane. 1987. "*Effet de l'Epandage des Eaux Usées Traitées et des Boues Résiduaires sur les Caractéristiques d'un Sol Sableux de Tunisie*" (in French). Science du Sol 25(4):267–78.

Bahri, A. 1995. "Environmental impacts of marginal waters and sewage sludge use in Tunisia." Paper presented at Pan-African Workshop on *African Women in Science and Engineering - A vision for the 21st Century*, Lund University, Sweden.

Bahri, A. and O. Mahjoub. 2007. "*Projet PISEAU I. Action de recherche: Utilisation agricole des boues résiduaires. Elaboration des norms*" (in French). Final Report. Institution de la Recherche et des Etudes Supérieures Agricoles, Institut National de Recherche en Génie Rural, Eaux et Forêts, Tunisie.

Berglund, K. and H. Claesson. 2010. "A Risk Assessment of Reusing Wastewater on Agricultural Soils - A Case Study on Heavy Metal Contamination of Peach Trees in Ouardanine, Tunisia." MSc dissertation, Report No TVVR - 10/5004 . ISSN: 1101-9824. Lund University, Sweden.

CNEA. 2008. "*Etude sur l'Etat de la Désertification pour une Gestion Durable des Ressources Naturelles en Tunisie*" (in French). Report on the third phase. Last Accessed: February 2008, http://www.chm-biodiv.nat.tn/sites/default/files/rapport_desertif.pdf.

CRDA. 2015. "Experience of the GDA of Ouardanine 2 in the Reuse of treated Wastewater" (in Arabic).

DGGREE. 2014. "*Evaluation de la Situation de la Réutilisation des Eaux Usées en Agriculture*" (in Arabic). Unpublished report.

DGGREE. 2015. "*Rapport sur la Situation des Périmètres Irrigués par les Eaux Usées Traitées*" (in French). Campagne 2014/2015.

Guardiola-Claramonte M., T. Sato, R. Choukr-Allah and M. Qadir. 2012. "Wastewater production, treatment and reuse around the Mediterranean Region: Current status and main drivers." In *Integrated Water Resources Management in the Mediterranean Region: Dialogue Towards New Strategy*, edited by Redouane Choukr-Allah, Ragab Ragab, and Rafael Rodriguez-Clemente, 139–174.

Hydro-plante. 2002. "*Etude d'Assainissement et de Recalibrage de l'Oued El Guelta*" (in French). Dossier d'éxecution, Tunisia.

Jiménez, B. 2007. "Helminth ova control in sludge: A review." *Water Science & Technology* 56(9): 147–55.

Jiménez, B., D. Mara, R. Carr and F. Brissaud. 2010. "Wastewater Treatment for Pathogen Removal and Nutrient Conservation: Suitable Systems for Use in Developing Countries." In *Wastewater Irrigation and Health. Assessing and Mitigating Risk in Low-Income Countries*, edited by P. Drechsel, C. A. Scott, L. Raschid-Sally, M. Redwood and A. Bahri, 149–170. Ottawa, Canada: IWMI and IDCR.

Keraita, B., F. Konradsen, and P. Drechsel. 2010. "Farm-Based Measures for Reducing Microbiological Health Risks for Consumers from Informal Wastewater-Irrigated Agriculture." In *Wastewater Irrigation and Health. Assessing and Mitigating Risk in Low-Income Countries*, edited by P. Drechsel, C. A. Scott, L. Raschid-Sally, M. Redwood and A. Bahri, 189–208. Ottawa, Canada: IWMI and IDCR.

National Institute of Statistics. 2015. "Census of population and housing in 2014, Tunisia." http://www.ins.nat.tn/indexen.php (accessed January 15, 2016).

United Nations Environment Programme (UNEP). 2005. *Water and Wastewater Reuse: An Environmentally Sound Approach for Sustainable Urban Water Management*. Osaka, Japan: UNEP and Global Environment Centre Foundation.

Vally Puddu, M. 2003. "*Diagnostic Technico-économique de la Réutilisation des Eaux usées Traitées dans le Périmètre de Ouardanine (Monastir-Tunisia)*" (in French). Tunisia: INRGRF.

World Health Organization (WHO). 2006. *WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater. Volume II: Wastewater in Agriculture*. Geneva, Switzerland: WHO-UNEP-FAO.

CASE 7

Effects of More Than 100 Years of Irrigation with Mexico City's Wastewater in the Mezquital Valley (Mexico)

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Abstract

The Mezquital Valley is a unique example of wastewater reuse due to its size (90,000 ha) and temporality (more than 100 years). In this region many data have been collected by several research groups. The aim of this case is to summarise the main lessons learned. This Soil-Aquifer-Treatment system developed as a consequence of the drainage of the closed basin of Mexico to avoid flooding in Mexico City. It has grown in response to the increase of the city's population and wastewater discharge volumes. Wastewater is a valuable resource in the semi-arid region north of Mexico City and its reuse enables the production of mainly fodder crops and maize, thus achieving above average yields. We investigated the effects of wastewater irrigation by sampling fields irrigated for different lengths of time, and by repeatedly monitoring single irrigation events. Results confirm that wastewater irrigation leads to a groundwater recharge of 25 $m^3\ s^{-1}$ (2.16 Mm day^{-1}). Although average maize productivity has increased from 2 t ha^{-1} under rain-fed

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agriculture to 10 t ha^{-1}, excess nitrogen is applied to the fields and leached as nitrate (up to 108 kg ha^{-1} under maize) or emitted as nitrous oxide (up to 0.34 mg N m^{-2} $hour^{-1}$ in maize fields). Heavy metals accumulate in the first 20 cm of the soil; however their availability to plants is small due to the alkaline pH values and the medium to large soil organic matter contents. Also pharmaceutical compounds accumulate in the top-soil, and an increase in the presence of antibiotic resistance genes was observed. Furthermore, an epidemiological study was conducted in this area in the 1990s, which indicated a larger prevalence of helminth infections among children in the irrigated area compared with a nearby area under rain-fed agriculture.

Until 2015, only untreated wastewater was applied to the fields, but in 2016 a large wastewater treatment plant will start to operate. We will therefore be able to monitor the changes in wastewater, soil, and crop quality and to evaluate the treatment performance and its effects on public health and environmental processes. Our experimental set-up and the archiving of samples make it possible to investigate the long-term effects of wastewater irrigation and yields robust information to derive guidelines for the safe use of wastewater in agriculture.

Keywords: irrigation, untreated sewage, environmental pollution, productivity, human health

1. Introduction

The Mezquital Valley, 80 km north of the metropolitan area of Mexico City, is an example of a low-cost Soil-Aquifer-Treatment system, in which 52 m^3 s^{-1} (4.49 Mm^3 day^{-1}) of untreated sewage and surface runoff are collected within the closed basin of Mexico to be used to irrigate agricultural land (Figure 1). At the beginning of the 20th century the discharged water was used first to generate electric power at two facilities within the valley. Its use for irrigation was officially permitted downstream of these facilities in 1912. As the discharge increased the irrigated land surface also extended, now reaching approximately 90,000 ha and benefitting more than 46,000 people in three irrigation districts (ID), namely ID-003 Tula, ID-100 Alfajayucan and ID-112 Ajacuba (Figure 1) (Conagua 2010).

The main crops are lucerne and maize, but also fodder oats, rape, ryegrass and some vegetables like zucchini, cauliflower and chili peppers are produced. The achieved mean maize yields of 10 t ha^{-1} are above the national averages obtained under rain-fed (2 t ha^{-1}) and well-water irrigated agriculture (8.6 t ha^{-1}) (Conagua 2010).

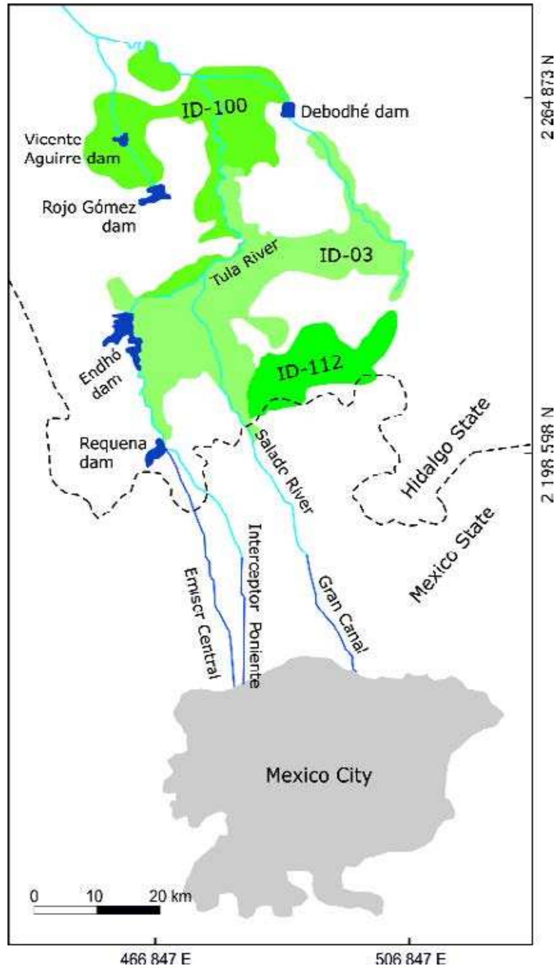

Figure 1: Location of the Mezquital Valley, north of Mexico City, and the three irrigation districts (ID): ID-003 (Tula), ID-100 (Alfajayucan) and ID-112 (Ajacuba) in which untreated wastewater from Mexico City is used for mean concentrations and standard deviations of distinct heavy metals and metalloids (N=9) (after Guédron et al., 2014) and concentration ranges of pharmaceutical compounds (N=12) (after Siemens et al., 2008) measured in the wastewater discharged into the Mezquital Valley are in UTM 14Q

The sewage is dominantly of domestic origin, has a mean content of total suspended solids of 295 mg L^{-1} and 264 mg L^{-1}, a chemical oxygen demand of 527 and 475 mg L^{-1} and a biochemical oxygen demand of 240 and 180 mg L^{-1}, respectively, in the dry and rainy seasons

(Jiménez and Landa 1998; Jiménez and Chávez 1997). It has large concentrations of organic matter (TOC: 35-188 mg L^{-1}), total nitrogen (37-38 mg L^{-1}) and phosphorous (2.7-3 mg L^{-1}), but also contains soluble salts (mainly NaCl and $NaHCO_3$) and thus has an electric conductivity of 1.4-1.7 mS cm^{-1}. Of great concern are the large concentrations of faecal coliforms (between 10^5 to 10^8 colony forming units, CFU/100 mL), *Streptococcus faecalis* (10^2 to 10^6 CFU/100 mL), *Clostridium perfringens* (10^3 to 10^6 CFU/100 mL), somatic bacteriophages (10^2 to 10^6 plaque forming units, PFU/mL), *Giardia spp*. (450 to 10,000 cysts/L), and helminth eggs (1.8 to 23 helminth eggs/L) (Navarro et al., 2015). Each irrigation event also adds heavy metals and pharmaceutical compounds in trace concentrations to the soils (Guédron et al. 2014; Gibson et al. 2007; Siemens et al. 2008) (Table 1).

Several investigations have been carried out in this region to analyse the effects of wastewater irrigation. This case aims to describe the current Soil-Aquifer-Treatment system and to review the main findings of different research groups concerning soil, crop and groundwater quality and public health in the area. Special emphasis is given to results obtained by sampling fields irrigated for different lengths of time over the last century, which makes it possible not only to understand the long-term effects of this practice, but also to help predict the behaviour of distinct soil and crop properties in the future. Additionally, the monitoring results of single irrigation events are reported, which helps to understand the functioning of the present Soil-Aquifer-Treatment system and derive recommendations to improve the current management practices and mitigate environmental damage.

At the end of the case the possible impact of a new wastewater treatment plant is discussed.

2. Description of the Current Soil-Aquifer-Treatment System

The Mezquital Valley has a semi-arid temperate climate, with a mean annual precipitation of 700 mm in the south and less than 400 mm in the north. Most of the rain occurs between June and September. Mean annual evapotranspiration is 1,800 mm. Before the current wastewater irrigation regime maize was produced under a large risk of drought

Table 1: Mean concentrations and standard deviations of distinct heavy metals and metalloids (N=9) (after Guédron et al. 2014) and concentration ranges of pharmaceutical compounds (N=12) (after Siemens et al. 2008) measured in the wastewater discharged into the Mezquital Valley

Element/ substance	Anatomical Therapeutic Chemical classification group (ATC2) of WHO	Concentration in wastewater
Al (mg L^{-1})	-	0.82 ± 0.03
As (mg L^{-1})	-	0.013 ± 0.007
Cd (mg L^{-1})	-	0.001 ± 0.001
Cr (mg L^{-1})	-	0.015 ± 0.001
Cu (mg L^{-1})	-	0.038 ± 0.002
Mn (mg L^{-1})	-	0.37 ± 0.01
Ni (mg L^{-1})	-	0.019 ± 0.003
Pb (mg L^{-1})	-	0.14 ± 0.01
Se (mg L^{-1})	-	0.005 ± 0.006
Zn (mg L^{-1})	-	0.80 ± 0.01
THg* (ng L^{-1})	-	363.4 ± 18.1
Trimetoprim (µg L^{-1})	antibacterials for systemic use	0.11 – 0.32
Clarithromycin (µg L^{-1})		0.07 – 0.12
Erythromycin (µg L^{-1})		<0.01 – 0.08
Metoprolol (µg L^{-1})	beta-blocking agents	0.21 – 3.10
Ibuprofen (µg L^{-1})	M1 anti-inflammatory and antirheumatic products;	0.22 – 0.54
Naproxen (µg L^{-1})		2.84 – 6.74
Diclofenac (µg L^{-1})		0.25 – 0.55
Sulfasalazine (µg L^{-1})		0.29 – 0.44
Bezafibrate (µg L^{-1})	C10 serum lipid-reducing agents	0.03 – 0.10
Gemfibrozil (µg L^{-1})		<0.01 – 0.22

*THg: Total particulate mercury

during the rainy season and with mean annual yields of less than 2 t ha^{-1}. Wheat, barley and beans were also cropped, but most of the land was used as extensive grasslands to feed sheep (Melville 1990).

Irrigation of fodder crops is performed by overflow, and maize is irrigated in furrows. It makes it possible to ensure yields during the rainy season, and to grow crops in the dry season. The land use system is a lucerne-maize rotation, where lucerne is grown for 3 to 5 years and then followed by 2 years alternating between maize in the spring-summer cycle and a second crop (such as fodder oats, barley or ryegrass) in the fall-winter cycle. Eventually maize is substituted by rape or by vegetables as zucchini, cauliflower or chili peppers. Since the mean monthly temperature does not fluctuate more than 2°C over the year (16 – 18 °C), lucerne can be cut every 45 days, i.e. 10 times per year yielding on average 100 t ha^{-1} of fresh biomass per year (25 t ha^{-1} dry mass; Siebe 1998, Conagua 2010).

The soils in the extended piedmonts and the valley bottom have formed on alluvial and colluvial deposits of the Quaternary age, which cover volcanic tuff deposits of the late Tertiary. Three main soil types can be found: Leptosols, Phaeozems and Vertisols (Siebe 1994a). The Leptosols have a silt loam to loam texture, are limited in depth to less than 25 cm by the volcanic tuff and eventually by a calcium carbonate enriched layer (caliche). The Phaeozems are loamy clay soils of medium depth (25 to 70 cm) while the Vertisols are generally deeper (100 to 120 cm) and have a more clay rich texture (Table 2). All these soils have a neutral to slightly alkaline pH, medium to large cation exchange capacities and medium organic matter contents (Table 2). Particularly the Phaeozems and Vertisols, which cover more than 65% of the valley, have large filter and buffer capacities (Siebe 1994a).

The Mezquital Valley has a three level aquifer and the one closest to the surface is recharged to more than 90% by the infiltrating wastewater according to isotope studies (Payne, 1975). Artificial groundwater recharge has been estimated at 25 $m^3 s^{-1}$ (2.16 $Mm^3 day^{-1}$) (British Geological Survey 1998).

Jiménez and Chávez (2004) analysed the efficiency of pollutant removal from the irrigation water by its infiltration through the soil at three different wells. The Soil Aquifer Treatment is particularly efficient in removing pathogens (>99.9% removal) such as *Salmonella spp.*, *E. hystolyitica* cysts, *Shigella spp.*, helminth ova and faecal coliforms. It also removes 100% of xylene, ethylbenzene, tetrachloroethylene, and chloroform. The total suspended particles are removed and the biochemical oxygen demand reduced by more than 97%. Heavy metals like Fe, Mn and Cr are removed at 88%, while Cu, Pb, As and Hg are removed at 52 to 80%. However, soluble salts, particularly nitrates, have been found to leach out of the soil and reach the groundwater (1.5 to 77 mg L^{-1} of nitrates; Jiménez and Chávez, 2004). Recently also several emerging pollutants have been measured in the wastewater (Table 1) and some of them, particularly acidic compounds such as naproxen, ibuprofen, diclofenac and sulfasalazine, were also found in shallow groundwater in concentrations ranging between 0.21-2.0, 0.51-0.6, 0.04-0.13, and 0.31-0.78 µg L^{-1}, respectively (Siemens et al. 2008).

Table 2: Mean Characteristics of the Soils in the Mezquital Valley

Soil type	Depth (cm)	Clay (%)	pH	Organic matter (%)	CEC ($cmolc kg^{-1}$)
Leptosol	23	23	7.5	3.8	20 – 32
Phaeozem	65	32	7.3	3.6	16 – 30
Vertisol	100	44	7.1	4.4	25 – 45

Source: Siebe 1994a

The recharged groundwater meets the regional mean for Mexican water quality criteria, and is used after chlorination to supply water to more than 700,000 inhabitants in the region. However, total and faecal coliforms, sodium, nitrate, mercury and lead concentrations exceed the maximum permissible limits at some wells and in particular sampling periods as reported by several authors, so that membrane filtration should be considered for its potabilisation (Jiménez and Chávez 2004).

2.1. Impacts on Public Health

In the 1990s the Mexican Institute for Public Health (INSP) in collaboration with the London School of Tropical Medicine conducted an epidemiological study in the area to investigate the prevalence of gastro-intestinal infections among farmworkers' families (Blumenthal et al. 1991-92; Blumenthal et al. 2000; Blumenthal et al. 2001, Cifuentes 1998). The study considered farmworkers' households in communities within the Mezquital Valley that use wastewater for irrigation and farmworkers' households in rain-fed agricultural areas for comparison. Among the impacts on human health, intestinal helminth infections represented the highest risk from exposure to raw wastewater. Wastewater irrigation was also associated with a higher risk of *Entamoeba hystolitica* infections in children, while the prevalence of other gastrointestinal infections, such as those produced by *Gardia lamblia*, were only partly related to exposure to untreated wastewater, with poor hygiene related to poverty conditions in non-irrigated areas of the region also determining the prevalence of gastro-intestinal infections (Cifuentes et al. 1991, Cifuentes et al. 2000, Siebe and Cifuentes 1995).

2.2. Effects on Soil and Crop Quality

As stated before, the soils in the region have a very good sorption capacity, due to their loamy to clayey texture, their medium to large organic matter contents and their neutral to slightly alkaline pH values. The sampling of fields that have been irrigated over different lengths of time, namely 0, 12, 23, 35, 50, 84 and 99 years, has shown that wastewater irrigation increases the soil organic matter contents by more than 60% during the first 30 to 40 years, until a new equilibrium between increased biomass production and its decomposition is reached (Figure 2a). The increased organic matter enforces the sorption capacity of these soils even further, since humified soil organic matter has the ability to adsorb not only nutrients but also pollutants.

The pH values tend to decrease slightly over time by about 1 pH unit, although the slope of the adjusted regression model is not significant, showing the great b uffer capacity of these soils. Nevertheless, the decrease in pH can be attributed to the protons produced by the nitrification of the ammonia nitrogen entering the soil with the wastewater, as the monitoring of several irrigation events has shown (Hernández et al. 2016).

The study of fields irrigated for different time periods also has revealed that heavy metals accumulate in the top soil, where they are

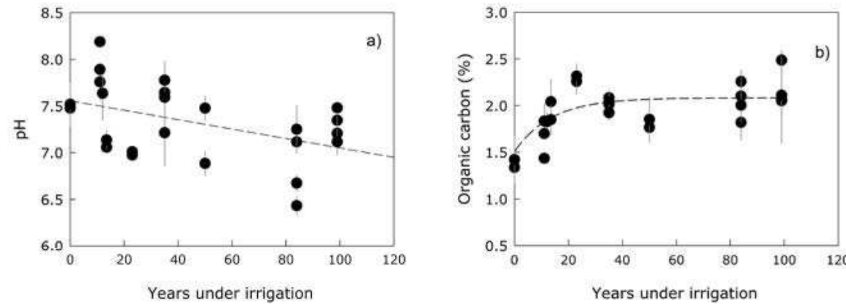

Figure 2: Behaviour of a) pH values and b) soil organic carbon contents in the upper 30 cm of the soil with length under irrigation (Chapela-Lara 2011). Error bars are 2 standard deviations.

dominantly bound to the soil organic matter (Siebe 1994b; Siebe and Cifuentes 1995; Chapela-Lara 2011; Guédron et al. 2014). Metal contents in soil increase linearly with time (Figure 3).

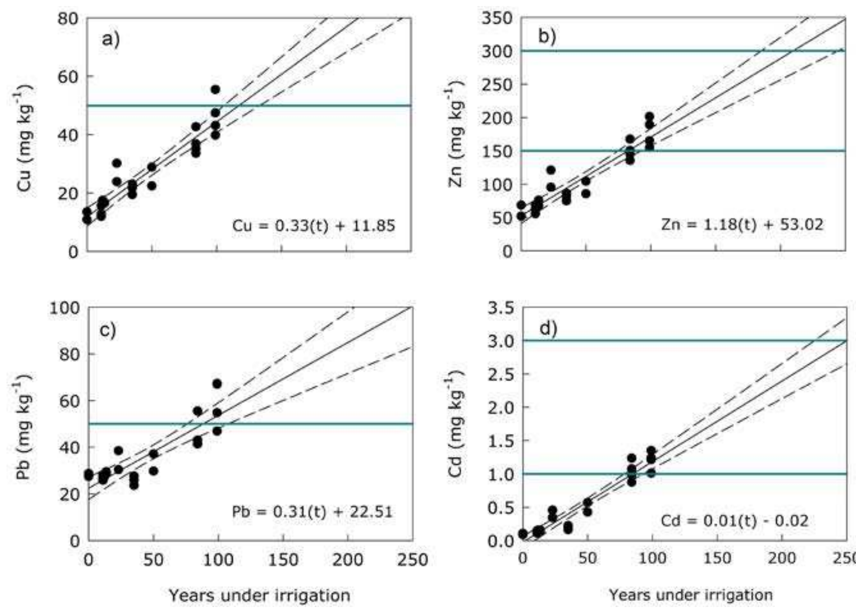

Figure 3: Behaviour of total contents of a) Cu, b) Zn, c) Pb and d) Cd in soil with length under irrigation (Chapela-Lara 2011).
Green horizontal lines indicate heavy metal reference concentrations or periods issued by the European Union for agricultural soils; the surpassing of these periods requires further studies to assess the mobility and plant availability of the contaminants (McGrath et al., 1994). A projection of a linear increase in time is also shown (black line, with the dotted lines representing 95% confidence).

The soil's adsorption capacity has been investigated in batch experiments in the laboratory; it resulted in being very large (Siebe and Fischer 1996) and increases with irrigation, which is attributable to the increase in soil organic matter contents.

In soils irrigated for 100 years, the total contents of Cu, Zn, Pb and Cd reached the lower threshold values established by European Union legislations for agricultural soils (Figure 3). The analysis of lucerne and maize grain confirmed that these metals are taken up by the crops in small quantities, and that the concentrations increase with the length of time under irrigation; however the maximum permissible limits for lucerne are still not reached, namely 0.5, 10, 20 and 50 mg kg^{-1} dry weight (DW) for Cd, Pb, Cu and Zn, respectively (WHO 1996) (Figure 4).

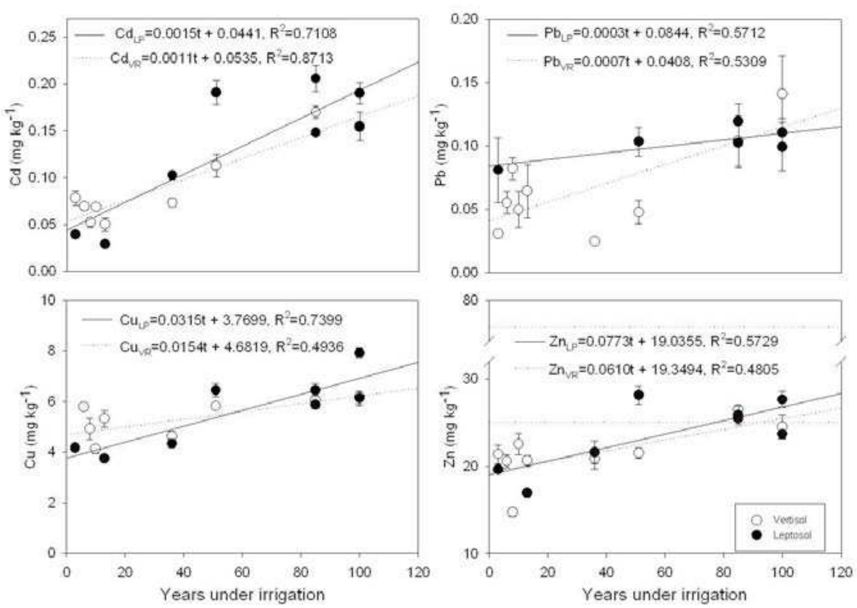

Figure 4: Heavy metal concentrations in lucerne in fields irrigated with wastewater for different lengths of time (Cayetano-Salazar 2012). VR: data from Vertisol fields; LP: data from Leptosol fields.

The adjusted regression models give an indication of when these maximum permissible limits are expected to be surpassed, namely in 304 to 406 years for Cd, 515 to 995 years for Cu, 400 to 500 years for Zn, and more than 14,200 years for Pb. On the other hand, the adjusted models can also be used to derive the concentrations that

these elements should not surpass in the wastewater, so that their inputs are balanced with the crop's up-take, and not accumulating in the soils over time. As can be observed in Table 3 these concentrations are by one to two orders of magnitude smaller than those established in the Mexican guidelines for irrigation water quality (Diario Oficial de la Federación 1997).

Table 3: Estimated concentrations of heavy metals in wastewater not accumulated in the soil over time and comparison with the maximum permissible concentrations according to the Mexican regulation

Metal	Concentration in irrigation water by soil type: Vertisol (mg L^{-1})	Leptosol (mg L^{-1})	Maximum permissible limits in irrigation water (mg L^{-1})
Cu	0.03	0.021	0.5
Zn	0.075	0.053	20.0
Pb	0.015	0.011	0.6

Source: Diario Oficial de la Federación 1997

The samples from fields irrigated for different lengths of time were also analysed for their concentrations of several pharmaceutical compounds, among them antibiotics, as well as for resistance genes to these antibiotics (Dalkmann et al. 2012). The concentrations of ciprofloxacin, sulfamethoxazole, and carbamazepine increased during the first 20 to 30 years. Then concentrations remained more or less constant at 1.4 µg/kg (ciprofloxacin), 4.3 µg/kg (sulfamethoxazole), and 5.4 µg/kg (carbamazepine), respectively. Diclofenac, naproxen, and bezafibrate did not accumulate in soils. These are acidic compounds that have a negative charge at the alkaline pH of the soils and therefore are not retained by the soil.

The resistance genes to flouroquinolones *qnrS* and *qnrB* genes were only found in two of the irrigated soils, while relative concentrations of resistance genes to sulphadiazines, such as *sul 1* and *sul 2* genes, were larger in irrigated soils than in non-irrigated soils. Absolute numbers of *sul* genes continued to increase by prolonging irrigation together with Enterococcus spp. 23S rDNA and total 16S rDNA contents. The increase in the total concentrations of antibiotics in the soil is not accompanied by an increase in the relative abundance of the investigated resistance genes. Nevertheless, wastewater irrigation enlarges the absolute concentration of resistance genes in soils due to a long-term increase in total microbial biomass.

2.3. Impacts of the Large Nitrogen Inputs to the System

Wastewater irrigation provides excess nitrogen to the crops. Mean annual N inputs to lucerne are 527 kg N ha^{-1}, and those of maize are 326 kg N ha^{-1} (Siebe 1998). Lucerne is a crop that does not depend on soil N sources, since it grows in symbiosis with bacteria which are capable of fixing atmospheric N. Maize is often fertilized with urea or ammonium sulphate by which an additional 120 to 180 kg ha^{-1} are supplied to the crop. We have investigated the fate of the large amounts of N entering this agroecosystem by monitoring single irrigation events (Hernández et al. 2016, González-Méndez et al. 2015) and calculating water and N balances. We have found that each irrigation adds up to 3.5 pore volumes of water to the soil, i.e. 2.5 times more water than the soil can retain. The surplus water drains shortly after irrigation into the subsoil and 5% of the irrigation reaches the aquifer. Within the soil there are preferential water flow paths, which transport solutes fast into deeper layers. Nitrogen enters the fields in the form of either ammonium (56%) or organic N (44%); part of the ammonium is temporarily adsorbed to clay minerals, but another part is readily transformed into nitrate, and leached into deeper soil layers and into the unsaturated zone beyond the roots. Some of the nitrogen is denitrified and emitted as either N_2O or probably even as N_2 into the atmosphere. González-Méndez et al. (2015) report mean N_2O emissions of 0.06 and 0.34 mg N m^{-2} $hour^{-1}$ from wastewater irrigated lucerne and maize fields, respectively. Also CO_2 emissions are increased in wastewater irrigated soils when compared with rain-fed soils (77.5 vs 16.6 mg C m^{-2} h^{-1}) due to enhanced microbial activity in the irrigated soils (González-Méndez et al. 2015).

3. Future Challenges

The most acute problem concerning the current SAT system in the Mezquital Valley is related to the increased risk of gastro-intestinal infections. Risk management has been carried out until now mainly through crop restriction, i.e. only fodder crops and large stem grains or vegetables are allowed and all vegetables that are in direct contact with the wastewater and the soil, and particularly those that are consumed raw, are prohibited. The risk of soil degradation through the accumulation of soluble salts is impeded by over-irrigation, which leaches salts out of the root zone and provides the above mentioned groundwater recharge.

In order to tackle the hygiene constraints that result from irrigating with untreated wastewater, and to fulfil the requirements already established since the 1990s in Mexican regulations, a large wastewater treatment plant is currently under construction, which should start operating in 2016 (Conagua 2011). It will treat 23 m^3 s^{-1} (1.99 Mm^3 day^{-1}) of urban wastewater from the MAMC by an aerobic biological activated sludge system; during the rainy season it will additionally have the capacity to treat 12 m^3 s^{-1} (1.04 Mm^3 day^{-1}) of surface run-off by advanced physic-chemical treatment. The investment costs are 751.1 million US dollars, 49% of which is provided by the federal government and 51% by private investors, and the estimated operation costs are 85.3 million dollars per year (equivalent to 0.12 USD/m^3 of biologically treated wastewater and 0.07 USD/m^3 of physic-chemically treated waste water). These costs will be charged to consumers in the MAMC through their potable water bills.

Among the expected benefits are reduced health risks, particularly of helminth infections, and an important reduction of organic matter and suspended particle contents, while most of the soluble N and P is expected to be maintained in the effluents so it can be recycled through irrigation. Chlorination of the effluent is supposed to minimise health risks further. This will presumably also allow cultivating vegetables that are consumed raw. Since the latter achieve much higher market prices, the income of farmers is also expected to rise. The reduction of suspended particles in the wastewater will also permit the use of drip irrigation, which significantly improves the efficiency of water use. Nitrogen inputs should also correspond to crop needs in this land use system. Optimised water use efficiency and smaller N loads should, therefore, also avoid nitrate leaching and N_2O emissions.

However, it is important to note that, in the medium term, this system will no longer contribute to the artificial aquifer recharge. In the future, other water sources of potable water for the inhabitants of the valley have to be explored. Also, important measures need to be undertaken to prevent soil salinisation, since the water treatment will most probably increase soluble salt concentrations. Special care should be taken to maintain the soil organic matter contents in order to prevent mobilisation of the pollutants currently retained on it. Another challenge will be the management of the produced sludge during water treatment. The current plan is to confine the dried sludge, but also its application as soil amendment is being considered, if the sludge meets the established threshold concentrations for inorganic and organic pollutants in the Mexican legislation (Diario Oficial de la Federación 2003). This scenario will implicate no change on the actual environmental risks of eutrophication and pollution mentioned before; it will rather most probably increase these risks, as the nutrient and pollutant loads will be much larger and occur in shorter time intervals, leading to larger disequilibria. Another concern is the formation of trihalomethanes, which will form as a consequence of the chlorination in combination with the remaining organic compounds, which will eventually not be eliminated completely by the wastewater treatment.

4. Lessons Learned and Future Research Needs

The current agricultural system has clearly improved crop productivity in this semi-arid region. The infiltrating wastewater has further recharged the aquifer, which is today a valuable water resource for the inhabitants. Soil Aquifer Treatment removes pathogens, suspended solids, organic matter and most pollutants very efficiently, but not the soluble salts, nor other soluble metal species such as organo-metallic Pb complexes, or soluble or negatively charged organic compounds and their metabolites. Excess nitrogen is applied to the fields by overflow irrigation, and although the current system uses nitrogen quite efficiently, the recharged groundwater is polluted with nitrate. Several pollutants, among them specially heavy metals but also some pharmaceuticals, accumulate in the top soil in the medium term and

are taken up by crops in small amounts. The study of soils irrigated for different lengths of time indicates that in the long term the current SAT system is not sustainable. Epidemiological investigations have also shown that farmers and their families living within the wastewater irrigation districts are at greater risk of suffering from gastro-intestinal infections, particularly by those pathogens that survive in the environment in form of cysts.

All these findings give a clear indication of the need to improve the on-going management system. Special care has to be given in the first place to the hygiene measures that farmers should undertake. The amount of water and nutrients provided to the fields also needs to be optimised. For this, field trials in which different management practices are tested and the water and nutrient balance is monitored can provide the required information. The study of fields irrigated for different lengths of time yields useful information that makes it possible to establish guidelines for the safer use of wastewater in this region and for other sites with similar soils.

The starting operations of the new wastewater treatment plant give a unique opportunity to test whether the large investment and operation costs of biological treatment are justified by a reduction in the incidence of gastro-intestinal infections. Our working group is currently performing an epidemiological study that aims to compare the incidence of diarrhea in children aged < 5 years in communities that are currently exposed to untreated wastewater and will soon switch to irrigate with treated wastewater. We will further continue monitoring the fields to measure the impact of water quality changes on the soil organic matter and the nitrogen balance of the system. Particular attention will also be given to the behaviour of heavy metals and organic contaminants as pharmaceuticals in the soil-aquifer-crop interface. Here also the relevance of the increased presence of resistance genes to antibiotic treatment deserves to be investigated.

References

Blumenthal, UJ, B. Abisudjak, E. Cifuentes, S. Bennett, G. Ruiz-Palacios. 1991–1992. "Recent epidemiological studies to test microbiological quality guidelines for wastewater use in agriculture and aquaculture." *Public Health Reviews* 19(1–4):237–242.

Blumenthal, UJ, DD Mara, A. Peasey, G. Ruiz-Palacios, and R. Stott. 2000. "Guidelines for the microbiological quality of treated wastewater used in agriculture: Recommendations for revising WHO guidelines." *Bulletin of the World Health Organization* 78(9):1104–16.

Blumenthal, UJ, E. Cifuentes, S. Bennett, M. Quigley, and G. Ruiz-Palacios. 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* 95(2):131–37.

British Geological Survey (BGS) and Comisión Nacional del Agua (can). 1998. "Impact of wastewater reuse on groundwater in the Mezquital Valley, Hidalgo State, México." Final Report. Keyworth, Nottinghamshire: NERC.

Cayetano-Salazar, M. 2012. "*Transferencia suelo-planta de metales pesados en parcelas regadas con agua residual en el Valle del Mezquital*" (in Spanish). Master Thesis. UNAM.

Chapela-Lara, M. 2011. "*Variación temporal en el contenido de metales pesados regados con aguas residuals*" (in Spanish). Master Thesis. UNAM.

Cifuentes, E. 1998. "The epidemiology of enteric infections in agricultural communities exposed to wastewater irrigation: Perspectives for risk control." *International Journal of Environmental Health Research* 8(3):203–13.

Cifuentes, E, U. Blumenthal, G. Ruiz-Palacois, and S. Bennett. 1991–1992. "Health impact evaluation of wastewater use in Mexico." *Public Health Reviews* 19:243–250.

Cifuentes, E, M. Gomez, U. Blumenthal, MM. Tellez-Rojo, I. Romieu, G. Ruiz-Palacios, and S. Ruiz-Velazco. 2000. "Risk factors for Giardia intestinalis infection in agricultural villages practicing wastewater irrigation in Mexico." *The American Journal of Tropical Medicine and Hygiene* 62(3):388–92.

Conagua (Comisión Nacional del Agua). 2010. "*Estadísticas agrícolas de los distritos de riego. Año 2007–2008*" (in Spanish). Secretariat of Environment and Natural Resources, México.

Conagua, 2011. "*Planta de Tratamiento de Aguas Residuales Atotonilco. Folleto emitido por la Comisión Nacional del Agua*" (in Spanish). Secretariat of Environment and Natural Resources, México.

Dalkmann, P, M. Broszat, C. Siebe, E. Willashek, T. Sakinic, J. Huebener, W. Amelung, E. Grohmann, and J. Siemens. 2012. "Accumulation of Pharmaceuticals, Enterococcus, and Resistance Genes in Soils Irrigated with Wastewater for Zero to 100 Years in Central Mexico." *PLoS ONE* 7(9): e45397.doi:10.1371/journal.pone.0045397.

Norma Oficial Mexicana. 1997. "*Establece los limites máximos permisibles de contaminantes en las descargas de aguas residuales en aguas y bienes nacionales*" (Maximum allowable limits of pollutants of wastewater discharges in national goods water bodies and soil). Diario Oficial de la Federacion, Mexico: NOM 001-ECOL-1996

Norma Oficial Mexicana. 2003. "*Protección ambiental.-Lodos y biosólidos.-Especificaciones y límites máximos permisibles de contaminantes para su aprovechamiento y disposición final.*" (Sludges and biosolids – characteristics and maximum permisible limits of pollutants for their user and final disposal.) *Diario Oficial de la Federacción*, Mexico: NOM-004-SEMARNAT-2002.

Gibson, R, E. Becerril-Bravo, V. Silva-Castro, B. Jiménez. 2007. "Determination of acidic pharmaceuticals and potential endocrine, disrupting compounds in wastewaters and springwaters by selective elution and analysis by gas chromatography-mass spectrometry." Journal of Chromatography A, 1169:31–39.

González-Méndez, B, R. Webster, S. Fiedler, E. Loza-Reyes, JM. Hernández, LG. Ruíz-Suárez, and C. Siebe. 2015. "Emissions of greenhouse gases from cropland irrigated with waste water: a case study in the Mezquital Valley of Mexico." *Atmospheric Environment* 101:116–24.

Guédron, S., C. Duwig, BL. Prado, D. Point, M. G. Flores and C. Siebe. 2014. "(Methyl) mercury, arsenic and lead contamination of the world's largest wastewater irrigation system: irrigation district of Mezquital valley (Hidalgo state – Mexico)." *Soil Water Air Pollution*, 225(8):2045–64.

Hernández, J L, B. Prado, M. Cayetano-Salazar, W. A. Bischoff, and C. Siebe C. 2016. "Ammonium-nitrate dynamics in the critical zone during single waste water irrigation events." Journal of Soils and Sediments (forthcoming).

Jiménez, B and A. Chávez. 1997. "Treatment of Mexico City Wastewater for Irrigation Purposes." *Environmental Technology* 18:721–30.

Jiménez, B and A Chávez. 2004. "Quality assessment of an aquifer recharged with wastewater for its potential use as drinking source: 'El Mezquital Valley' case." *Water Science and Technology* 50:269–76.

Jiménez, B. and Landa, LH. 1998. "Physical-chemical and bacteriological characterization of wastewater from Mexico City." *Water Science and Technology* 37:1–8.

McGrath, SP, AC. Chang, AL. Page, and E. Witter. 1994. "Land application of sewage sludge: scientific perspectives of heavy metal loading limits in Europe and the United States." *Environmental Reviews* 2:108–18.

Melville, E G K. 1994. *A Plague of Sheep: Environmental Consequences of the Conquest of Mexico*. Cambridge and New York: Cambridge University Press.

Navarro, I, A. Chávez, JA. Barrios, C. Maya, E. Becerril, S. Lucario and B. Jiménez. 2015. "Wastewater reuse for irrigation. Practices, Safe Reuse and Perspectives. Case 2." In *Irrigation and Drainage. Sustainable Strategies and Systems*, edited by Muhammad Salik Javaid. InTech.

Payne, B. 1975. "La interacción del agua de riego con el agua subterránea y el río Tula en el Valle del Mezquital. Informe final" (in Spanish). IAEA Isotope Hydrology section.

Siebe, C. 1994a. "*Akkumulation, Mobilität und Verfügbarkeit von Schwermetallen in langjährig mit städtischen Abwässern bewässerten Böden in Zentralmexiko*" (in German). *Hohenheimer Bodenkundliche Hefte* 17. Hohenheim: Hohenheim Verlag.

Siebe, C. 1994b. "*Acumulación y disponibilidad de metales pesados en suelos regados con aguas residuales en el distrito de riego 03, Tula, Hidalgo, México*" (in Spanish). *Revista Internacional de Contaminación Ambiental* 10:15–21.

Siebe, C. 1998. "Nutrient inputs to soils and their uptake by alfalfa through long-term irrigation with untreated sewage effluent in Mexico." *Soil Use and Management* 13:1– 5.

Siebe, C and E. Cifuentes. 1995. "Environmental Impact of Wastewater Irrigation in Central Mexico- An overview." *International Journal of Environmental Health Research* 5 (2):161–73.

Siebe, C and WR. Fischer. 1996. "Adsorption of Pb, Cd, Cu and Zn by two soils of volcanic origin under long term irrigation with untreated sewage effluent in Central Mexico." *Journal of Plant Nutrition and Soil Science* 159:357–64.

Siemens, J, G. Huschek, C. Siebe, and M. Kaupenjohann. "Concentrations and mobility of human pharmaceuticals in the world's largest wastewater irrigation system, Mexico-City-Mezquital Valley." *Water Research* 42 2008:2124–34.

World Health Organization (WHO). 1996. *Trace elements in human nutrition and health*. Geneva: WHO.

CASE 8

Eco-Friendly Wastewater Treatment for Reuse in Agriculture (India)

Ravinder Kaur [1]

Abstract

Oxidation ponds or activated sludge processes are the two most commonly deployed wastewater treatment technologies in India. However, these processes are expensive and require complex operations and maintenance. In view of these limitations, constructed wetland technology has been receiving greater attention in recent years. However, the rate of adoption of wetland technology for wastewater treatment in developing countries has been low due a general belief that these technologies have large land area requirements. Batch-fed wetland systems with shorter hydraulic retention times (HRTs) have generally been found to translate into smaller land requirements and thus appear more acceptable in developing countries. Keeping this in mind, a batch-fed (<1-day HRT) municipal wastewater treatment plant with vertical sub-surface flow wetland technology and a 1,500-LPD capacity was developed at the sewage plot site of the Indian Agricultural Research farm. The pilot plant has been in operation since November 2009 and is being continuously monitored for nutrient/heavy metal (pollutant) mass reduction efficiencies. The long-term average pollutant mass reduction efficiency of the pilot system illustrated its capacity to reduce wastewater turbidity and nitrate, phosphate, and

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potassium concentrations by up to 81%, 68%, 48% and 47%, respectively. Planted wetland systems, in general, seemed to have an edge over unplanted ones. Nutrient removal efficiencies seemed to be higher for *Phragmites karka* based wetland systems. The *Typha latifolia* based systems, on the other hand, were observed to be associated with a higher oxidation potential and thus higher sulphate reduction efficiencies (50.51%). These systems also seemed to be associated with significantly higher Ni (62%), Fe (45%), Pb (58%), Co (62%) and Cd (50%) removal efficiencies. A comparison of the ecological footprint and sustainability of the experimental wetland systems compared with a hypothetic conventional sewage treatment plant (STP) showed that the experimental wetland systems were 1,500 times more sustainable. Based on these experiences, the technology has been recently up-scaled to a 2.2 MLD horizontal sub-surface flow system for treating sewage waters in the Krishi Kunj colony adjoining the Indian Agricultural Research Institute (IARI) campus. The up-scaled system has the potential to irrigate 132 ha of land on the Indian Agricultural Research farm.

Keywords: engineered wetlands, energy, eco-budgeting, sustainability, phyto-remediation

1. Background

Freshwater scarcity, the generation of increasing volumes of wastewater, the degradation of freshwater resources, and the interconnected food insecurity, due to rapid urbanisation/industrialisation, are driving many countries to use marginal-quality water in agriculture. Agricultural reuse of wastewater is fast becoming popular worldwide because it closes the loop between water demand and wastewater disposal and enhances fertilizer security as a resource for poor farmers. However, due to the lack of proper treatment facilities and awareness in developing countries, the unplanned application of wastewater/raw sewage is increasing the risk of agricultural sustainability and consumer/environmental health. Thus for safe agricultural disposal (with optimum profit), the safe, economic and effective treatment of sewage is one of the most challenging problems faced worldwide.

Oxidation ponds or activated sludge processes are the two most common methods of municipal wastewater treatment in India. These processes are expensive and require complex operations and maintenance. Furthermore, due to improper design, poor maintenance, frequent electricity breakdowns and/or a lack of technical manpower, these conventional wastewater treatment facilities do not function properly and therefore remain closed most of the time. In view of these limitations, in recent years, constructed wetland technology (Mitsch and Gosselink 2007) has been receiving greater attention. However, its rate of adoption in developing countries has been quite low (Denny 1997), primarily due to a general belief that these technologies have large land area requirements. Wetland systems with shorter hydraulic retention times (HRTs) have generally been found to translate into smaller land area requirements. Furthermore, such batch-fed systems (with increased detention times) have been reported to be associated with not only lower treatment areas (Mehrdadi et al. 2009) but also higher pollutant removal efficiency. This has been observed to have had an implication on their greater acceptability in developing countries like India. However, such batch-fed wetland systems, with < 1-day HRT, have not been extensively tested across tropical developing countries so far.

Keeping the aforementioned facts in, mind a constructed wetland technology-based pilot plant was developed at the wastewater irrigated plot site of the Indian Agricultural Research Institute (IARI) farm, with the basic aim of assessing its a) pollutant removal efficiency and upscale potential for augmenting IARI-farm irrigation water supplies, and b) ecological footprint and sustainability compared with a conventional sewage water treatment plant.

2. The Pioneering Initiative

In view of the aforementioned limitations, a business model-integrated, innovative, de-centralised, energy-efficient and eco-friendly wastewater treatment technology was conceptualised and developed between 2009 and 2011 and later up-scaled between 2011 and 2013, for managing urban wastewater discharge from the Krishi Kunj/Loha Mandi colony and its reuse for irrigation/aquaculture on the Indian Agricultural Research Institute (IARI) campus.

2.1. Situation Prior to the Initiative

The IARI campus is located at the heart of the National Capital Territory (NCT), Delhi (India), and is crossed by a network of sewage drains whose total discharge amounts to about 700 ha m/year (or about 20 MLD). These sewage drains receive domestic and industrial effluents generated by the residential areas adjoining/within the IARI campus and a complex combination of industrial and commercial units around the IARI micro-watershed.

Prior to the initiative, the urban (untreated) wastewater stream, flowing out of the Krishi Kunj and Loha Mandi colonies, crossed the Indian Agricultural Research Institute farm to ultimately merge with the nearby Loha Mandi drain (an off-shoot of the Najafgarh drain) and the Yamuna river. The wastewater stream was found to be associated with inter-seasonal turbidity levels of 200 to 1,000 NTU; BOD levels of 230 to 730 ppm; 3 to 28 ppm phosphate, 0.1 to 12 ppm nitrate, 11 to 99 ppm sulphate, 0.1 to 1.3 ppm nickel, 1.5 to 2.3 ppm chromium, 0.05 to 0.28 ppm lead, 0.31 to 4.65 ppm zinc, and 0.41 to 23.60 ppm iron. Besides causing extensive mosquito breeding in the farm area and the urban neighbourhood, continuous ponding of this wastewater was also reported for extensive soil/groundwater degradation in the IARI farmlands. A detailed analysis of total heavy metal pollution in the local farm area (through which this untreated urban wastewater stream was flowing) revealed 1.53 times more than the permissible level of total chromium (253.27 mg/kg), 0.97 times more than permissible level of zinc (393.63 mg/kg), 3.09 times more than permissible level of copper (122.65 mg/kg) and 1.30 times more than permissible level of lead (80.44 mg/kg) in the farm soils and 11.5 times more than permissible level of chromium (1.25 ppm) in the local groundwater.

Thus, though there was a voluminous wastewater stream (daily discharge of 2.2 million litres) flowing through the farm area, which could easily bridge the gap between the total demand for farm irrigation water (1,800 million litres per year) and the available groundwater supply (1,280 million litres per year), it was of little use due to its contamination with many organic/inorganic pollutants and heavy metals.

2.2. Specific Objectives of the Initiative

Against the backdrop of an acute water shortage, on the one hand, and the availability of an appreciable volume of an untreated urban wastewater stream in the farm area, on the other hand, which could be recycled and reused for safe farm irrigation (after its appropriate treatment), a study was initiated to:

- Devise an innovative, low-cost, and energy-efficient decentralised urban wastewater treatment technology;
- Compare its ecological footprint with a comparable (hypothetic) conventional wastewater treatment plant;
- Assess the impact of wastewater treated in this way on soil health and agricultural produce; and
- Integrate the developed decentralised wastewater treatment technology with an appropriate business model for long-term self-sustainability and wide-scale adoption in peri-urban/urban areas.

2.3. Implementation Process

The technology was implemented via following stages:

Stage I (Piloting)
The proposed initiative stems from a pilot comprising 16 small-scale batch-fed vertical sub-surface flow experimental wastewater treatment cells (i.e. mesocosms, each with a 500 litre capacity), which were developed in 2009. These were planted with 4 replicates of 3 emergent vegetations (such as *Phragmites karka, Acorous calamus* and *Typha latifolia*) on diversified stratified media beds or left as non-vegetated controls for assessing their comparative nutrient and metal reduction efficiency and thereby screening an appropriate vegetation and media combination with promising pollutant reduction efficiency. The mesososms were connected to the individual inlet pipes from the main (sewage water) influent discharge line, through ball valves to hydraulically maintain a maximum water level of 15.24 cm (or 6 inches) above media, at each flooding event. A diagrammatic representation of the layout and the flow path of the pilot is shown in Figure 1. Influent and effluent water samples were periodically sampled and analysed in

triplicate, as per the standard estimation procedures, with due quality control ensured through careful standardisation, procedural blank measurements and duplicate samples.

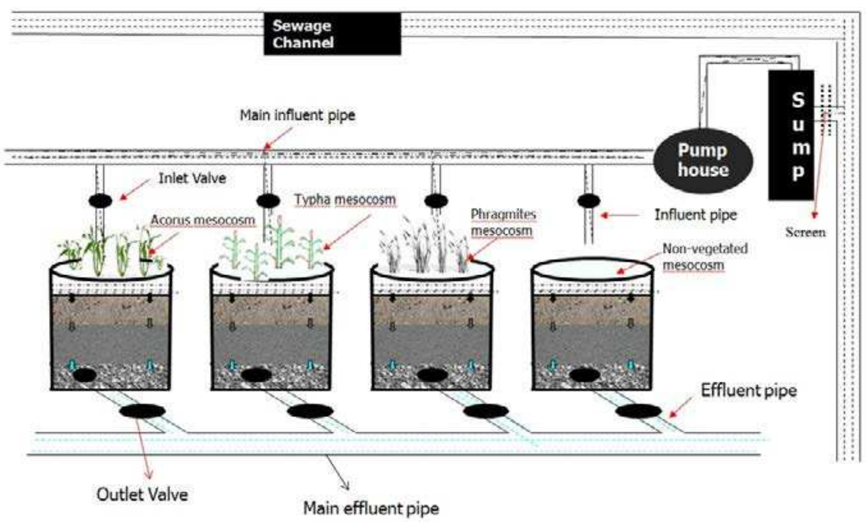

Figure 1: Layout of a pilot urban wastewater treatment system

Long-term monitoring (from 2009 to 2011) of the pollutant reduction efficiency of these systems demonstrated that *Typha latifolia*-based systems had an edge over the other systems, particularly in terms of nitrate (90.74%), phosphate (77.65%) and potassium (48.57%) removal efficiencies. *Typha latifolia*-based systems, associated with the highest oxidation potential, were also associated with the highest sulphate reduction efficiencies (65.41%). In general, the gravel media-based systems planted with *Typha latifolia* seemed to be associated with significantly higher nickel (70-74%), lead (53-63%), and other trace metal removal efficiencies. These were also observed to be the best chromium sequesters and associated with significantly higher BOD and ORP reduction rates, and hence the most promising wastewater treatment systems.

The long-term environmental impacts of treated and untreated sewage water irrigation on soil health, crop yield, seed vigour and food grain contamination (during both the Rabi and Kharif seasons) were also assessed.

<u>Stage II (p-scaling)</u>

Subsequently, the validated technology was up-scaled in March 2011 to treat urban wastewater from the Krishi Kunj/Loha Mandi colonies.

Meanwhile, during 2010-11, a detailed temporal account of the quantity and quality of the wastewater (i.e. total/inter-seasonal pollutant load) flowing out of the Krishi Kunj/Loha Mandi colonies, along with the available land area and spatially variable (gridded) soil quality profile of the project site (as detailed in the section "Situation prior to the initiative") were assessed.

The aforementioned land and water quality information was thereafter used to develop a detailed design of the wastewater treatment facility (during February-March 2011) and to work out the design of hydraulic retention times (HRTs) for remediating 2.2 million litres per day of incoming wastewater streams to the target permissible pollutant levels for safe land application. The aforementioned HRTs were optimised for the different pollutant loading rates observed at the project site. The construction of the optimised design started in September 2011 (subsequent to a work contract floated in March 2011) and ended in April 2013.

Figure 2: Panoramic view of the proposed (up-scaled) eco-friendly municipal wastewater treatment plant and its components

The wastewater treatment plant comprises of 3 treatment cells (each of 80 m by 40 m), where innovative organic, nutrient and metal pollutant reductions (i.e. secondary and tertiary treatments) take place, as well as 2 sewage wells and 1 grit chamber, where preliminary/primary treatment takes place (Figure 2). The treated waters are collected in three individual sumps, located on the outlet side of each treatment cell. These are interconnected with each other to allow gravity flow of the entire treated water stream to a common collector sump, located adjacent to a large (80 m by 40 m by 2 m) treated water collection tank. The facility is spread over 1.42 ha of land. The sewage wells, grit chamber, first wastewater treatment cell and the treated water collection tank were operationalised in September 2012 while the other 2 treatment cells and part of the IARI irrigation network were operationalised in May 2013.

To make the whole system energy intensive, a complete gravity flow of the wastewater, from the grit chamber to the treated water collector sump of the system was ensured. Each treatment cell is stratified with a design bed of gravels of varying sizes/grades, onto which the pilot-tested and promising *Typha latifolia* hyper-accumulating emergent vegetation is planted at design intensity, depths and distances. The planted vegetation has the ability to transfer oxygen from its leaves, down through its stem, and rhizomes, and out via its root system, into the rhizosphere (root system) and hence requires no 24x7 operation of (energy-extensive) aerators, such as those generally used in conventional wastewater treatment plants. As a result of this natural ingress of ambient oxygen into the treatment cells, a very high population of native micro-organisms (generally present in wastewater) tends to be naturally bio-augmented in the root zone of the planted vegetation, where most of the organic and inorganic (i.e. nutrient and metal) transformations take place, thereby further ruling out the need for the incorporation of any external bio-inoculants or any chemical-based consumables and thus making the whole wastewater treatment process completely eco-friendly, less energy-intensive and associated with no sludge generation. The flow of the wastewater in each treatment cell is regulated so that there is complete sub-surface flow, thereby leading to no ponding, foul smell, mosquito breeding, or any direct contact with wastewater. Thus, with the wastewater moving at design depth and flow rate through the root mass of this emergent vegetation and its interaction with native micro-organisms and planting media, various organic/inorganic pollutants and heavy metals in the wastewater are transformed, sequestered and removed from the treatment zone – thereby remediating the wastewater. The treated water is finally

collected in an 80 m by 40 m by 2 m treated water collection tank, from where it is finally pumped, through a riser and a set of hydrants, into the irrigation network of the Indian Agricultural Research Institute farm.

Stage III (Technical and economic evaluation and operationalisation)

The developed decentralised urban wastewater treatment plant, the first (and largest) of its kind in the country (see Google Maps image), has been continuously monitored for its nutrient and metal reduction efficiencies since September 2012 and was opened to the public after its long-term validation and formal inauguration by the Union and the State Ministers of Agriculture on July 2, 2014.

To integrate a good business model with the proposed decentralised wastewater treatment technology and to make the system completely self-sustained, the emergent hyper-accumulators planted in the treatment cells of the proposed facility were harvested and assessed technically and economically for their potential to be transformed to particle board – a good substitute for wood (Figure 3), in collaboration with a private partner.

Figure 3: Transformation of harvested biomass into particle board – a cash-from-trash business model integrated with the proposed urban wastewater treatment initiative

Finally, the economic benefits and the CAPEX and OPEX of the proposed initiative over and above a comparable (hypothetic) conventional sewage treatment plant (STP) were assessed.

Furthermore, an energy-based analysis – a comprehensive environmental accounting technique (Odum 1996) – was used for assessing and comparing the ecological efficiency and sustainability of the conventional and proposed initiatives in terms of a number of energy indices such as the Environmental Load Ratio (ELR), Energy Sustainability Index (ESI) and the Percent Renewable (PR) indices.

3. Significant Outputs of the Initiative

3.1. Treatment Efficiency

Long-term monitoring of the treatment capacity of the developed wastewater treatment plant could reveal its exceptional performance (Figure 4), especially regarding Turbidity (99%), BOD (87%), Nitrate (95%), Phosphate (90%), Lead (81%), and Iron (99%), and also in terms of a number of other pollutants, such as Nickel (59%), Zinc (58%), and Sulphate (48%), that were normally present in moderate concentrations in proposed urban wastewater systems.

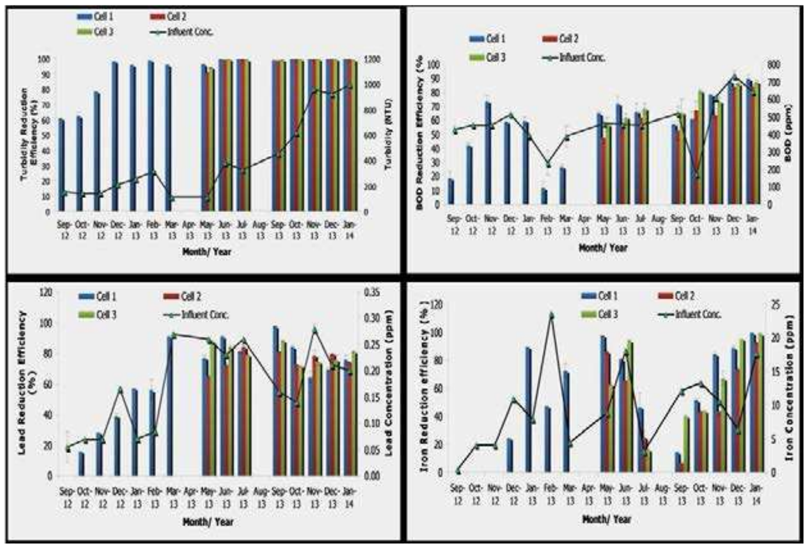

Figure 4: Pollutant reduction efficiency of the proposed urban wastewater treatment initiative

A comparison of the treated wastewater with local groundwater samples from the IARI farm further showed (Figure 5) that the treated wastewater (with legend: E-STP) was associated with either better or identical EC, pH, turbidity, nitrate, sulphate, phosphate and metal concentrations than those for the groundwater of the surrounding farm areas (viz. SPU, MB1A and STP).

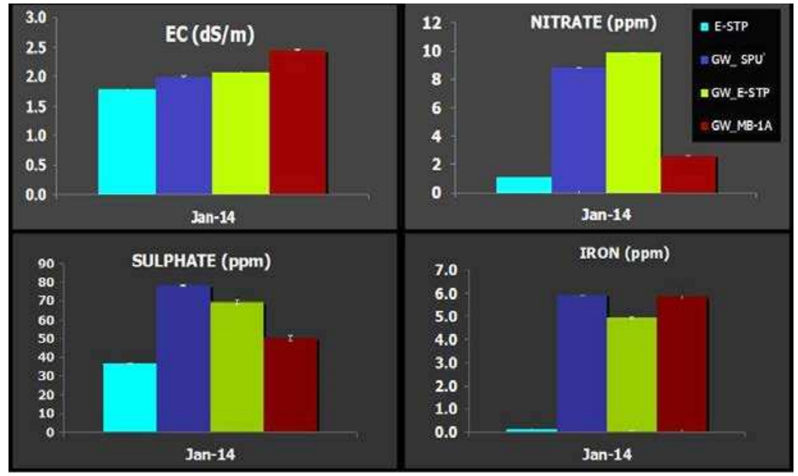

Figure 5: Quality of treated wastewater (e-STP) vs. local groundwater on the Indian Agricultural Research Institute farm

3.2. Impact Assessment

3.2.1. Soil Health

The continuous application of treated sewage waters, in place of untreated sewage water applications at the project site resulted in significant reductions in soil total and bio-available nickel, lead and iron concentrations (Figure 6). Soil bio-available chromium also decreased from an initial level of 5.71 ± 0.88 mg/kg to 1.57 ± 0.07 mg/kg within two years. Thus, continuous irrigation with treated sewage water led to significant reductions in the soil pollutant load. However, these were associated with no soil micro-nutrient depletion and no adverse effects due to soil electrical conductivity and the exchangeable sodium percentage, which remained within safe limits.

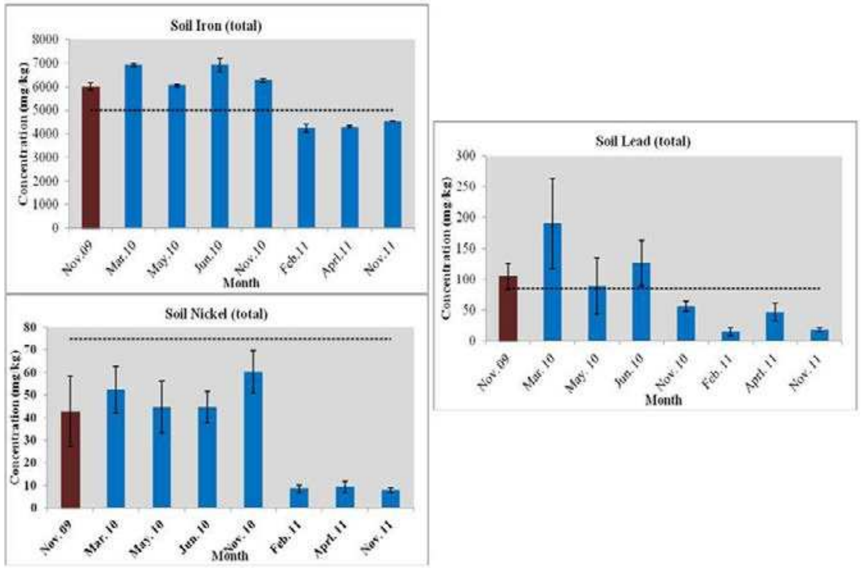

Figure 6: Long-term environmental impact of treated sewage water irrigation on soil health

3.2.2. Crop Health and Quality

The impact of the untreated and treated sewage water on the health and quality of wheat and paddy crops was also estimated in terms of plant/seed parameters, individual metal translocation patterns, and the food grain metal sequestration threat. The positive impact of water treatment could be best expressed in terms of the test weight or 100 seed weight of the paddy crop, as it was found to be significantly lower for the crop irrigated with wastewater. Furthermore, though the total number of tillers and the length of panicles were not significantly different for the treated and untreated sewage water, the total number of unproductive tillers and unfilled seeds per panicle were significantly higher in the paddy crop irrigated with sewage water. These differences were not very evident in a relatively low water-demanding crop such as wheat. However, a number of tillers infected with termites and fungi in both wheat and paddy crops were observed to be higher in the micro-plots irrigated with sewage water.

3.2.3. Metal Translocation and Food Grain Contamination

Individual metal translocation patterns in the wheat and paddy crop plants revealed a higher food grain metal sequestration threat in wheat. The analysis showed that the overall metal health hazard (as is evident from Hazard Index, Figure 7) due to the consumption of wheat grains produced through the use of untreated wastewater on the historically metal-contaminated soils was about 1.6 times more than that due to the consumption of paddy grains. About 45 to 60% of these health hazards were contributed to by lead contamination. In general, food grains produced through (lead-sequestering) Phragmites karka-treated wastewater were observed to be associated with 44 to 58% fewer health hazards. From a health point of view, the agricultural produce from the sewage plot sites was still not suitable for human consumption; especially due to considerable food grain metal, i.e. lead >> iron > nickel ~ Mn contamination. However, these risks were far below those observed in previous years, primarily due to the continuous application of treated sewage waters.

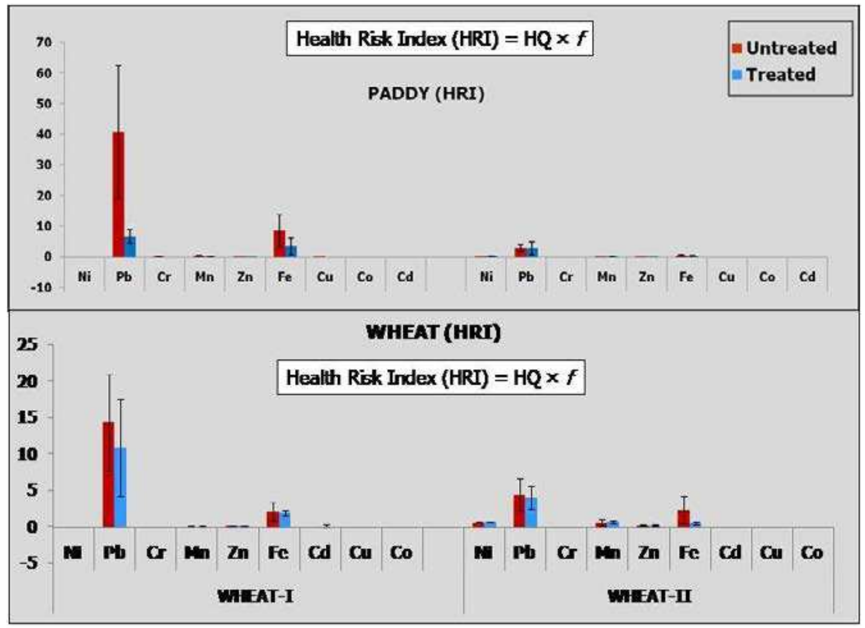

Figure 7: Impact of treated and untreated sewage water on food grain metal-based consumer health risks

3.2.4. Benefits

An energy analysis of the proposed initiative (Table 1) showed that renewable resources constituted 54.24% of total energy use, with the other half (i.e. 45.76%) contributed by purchased non-renewable resources such as construction, electricity and maintenance. In the renewable (i.e. local + purchased) resource category, the local (i.e. free) renewable resources contributed the most (77.69%) energy. Purchased renewable resources such as the media and the vegetation, which require servicing to access, constituted only 12% of total energy use and were thus a minor source of total system energy use. In the purchased non-renewable resource category, labour-intensive purchased services such as construction (63.26%, with an assumed life span of 20 years) and annual maintenance (36.47%) contributed most while electricity contributed least (0.27%).

Table 1: Energy budgeting of proposed initiative vs. conventional STP

INPUTS	SOLAR ENERGY (sej/yr)	
	Proposed Initiative	Conventional STP
Local renewable resources	1.14 X 10^{16}	1.82 X 10^{16}
Purchased renewable resources	3.27 X 10^{15}	0.00
Purchased non-renewable resources	3.97 X 10^{16}	7.68 X 10^{17}
Purchased resources	4.30 X 10^{16}	7.68 X 10^{17}
Total resource use	5.44 X 10^{16}	7.87 X 10^{17}

In contrast with the proposed initiative, a comparable (hypothetic) sewage treatment plant was observed to be associated with far higher (98.26%) purchased non-renewable resource energy use. The contribution of total energy use by the non-renewable resources in a conventional STP was about 83 times more than that in a (comparable) proposed initiative. Amongst the purchased non-renewable resources, operational costs such as maintenance (48.10%) and electricity (28.31%) contributed the most (76.41%), with the remaining 23.59% contributed by construction (with an assumed life span of 20 years).

A comparison of the proposed initiative with a comparable conventional STP thus revealed clear electrical usage advantages, as electrical energy consumption was observed to be less than 1% of a conventional sewage treatment plant. Furthermore, the analysis indicated that the proposed initiative required simpler maintenance as the system has no demand for any consumables and largely relies on the ecological action of (native) microbes and plants for their efficacy.

Thus, in terms of standard cost-accounting, the proposed initiative was found to be associated with Rs. 0.545 Crore per MLD of capital cost (CAPEX) and about Rs. 0.607 per lilolitre (KL) of total operational and maintenance costs. In comparison with a comparable conventional wastewater treatment plant (Table 2), the proposed initiative was thus observed to be associated with about 50-65% lower treatment costs.

Table 2: Sustainability of the proposed initiative vs. conventional STP

Energy Indices	Proposed Initiative	Conventional STP
Energy Yield Ratio	0.70	0.01
Environment Loading Ratio	1.37	42.19
Renewable Percentage	0.54	0.02
Energy Sustainability Index	0.51	0.00034

A comparison of the proposed eco-friendly wastewater treatment system with a conventional wastewater treatment plant showed that the proposed technology is associated with an energy requirement of below 1%, zero-chemical application, zero-sludge generation, 50-65% reduced treatment costs, and no skilled manpower requirements.

3.3. Sustainability of the Project Initiative

The ecological efficiency and sustainability analysis of the proposed initiative, in terms of a number of energy indices (Table 2), showed that it utilises 27 times more renewable resources than a conventional sewage treatment plant and is thus 1,500 times more sustainable than a conventional STP. Furthermore, the proposed initiative was found to cause 33 times less environmental stress than a comparable conventional sewage treatment plant.

Additionally, the vegetation planted in each treatment cell of the proposed fully operational wastewater treatment system could be harvested (once every two months) to yield 36 tons of dry biomass per annum (Figure 3). This could be successfully transformed to a (termite and waterproof) particle board (9,000 sq. meters per annum; market price Rs. 200-250/sq. meter) or sold to the local particle board manufacturers (at Rs. 2000 per ton) as dry matter – thereby fetching a maximum annual income of about Rs. 18 lakh per annum and integrating a perfect cash-from-trash business model with the proposed initiative.

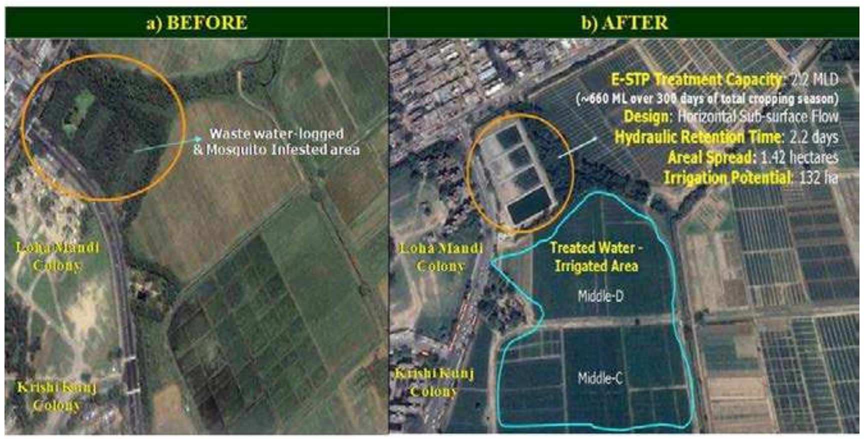

Figure 8: Satellite view of the project site (a) before and (b) after the proposed initiative

4. Conclusions

The proposed initiative could thus create a good-quality annual local surface water source of about 660 million litres and could thus stop the practice of purchasing contaminated surface water (at Rs 18.5 lakh per annum), from the Bhuli-Bhatiyaari drain, to meet the irrigation water demand of IARI farmland. The initiative could thus, in addition to resulting in an annual saving of about Rs 18.5 lakh and bridging an annual gap (of 520 ML) between irrigation water demand and supply on IARI farmland, lead to effective urban wastewater management and sanitation, with no foul smell or mosquitos breeding in the area. In fact the project site, which used to be completely unapproachable (Figure 8), now looks like an eco-park and is frequently used by residents as a favourite site for morning walking/jogging. The facility has already resulted in considerable tangible savings due to the discontinuation of purchased contaminated surface water for irrigating IARI farmland. From an intangible perspective, it is expected that a continued combined use of the treated water source, along with the existing groundwater source, will replenish receding groundwater aquifers not only at IARI but also in the neighbouring urban area. On a long-term scale, this is expected not only to reduce total energy use with respect to groundwater extraction but also significantly improve soil/groundwater quality and productivity on IARI farmlands.

References

Denny, P. 1997. “Implementation of constructed wetlands in developing countries.” *Water Science Technology* 35:27–34.

Mitsch, W.J. and J.G. Gosseink. 2007. *Wetlands.* 4th edition. New York: John Wiley.

Mehrdadi, N., A. Rahmani, A.A. Azimi, and A. Torabian. 2009. “Study of operation subsurface flow wetland in batch flow system for municipal wastewater treatment.” *Asian Journal of Chemistry* 21(7):5245–50.

Odum, II.T. 1996. *Environmental Accounting: ENERGY and Decision Making.* New York: John Wiley.

CASE 9

Productivity of Sugarcane Irrigated with Effluent from the Cañaveralejo Wastewater Treatment Plant in Cali, Colombia (Colombia)

C. A. Madera-Parra, A. Echeverri, and N. Urrutia [1]

Abstract

In Valle del Cauca, southwest Colombia, surface and ground water is used for sugarcane irrigation at a rate of 100 m^3/ton of sugar produced. Preliminary experiments were carried out to determine the effect on the sugarcane (variety CC-8592) yield irrigated with effluent from the Cañaveralejo primary wastewater treatment plant (PTAR-C) in Cali. Irrigation was applied for one year on a 0.36 ha plot. Two water sources were used: effluent from PTAR-C and groundwater (GW). A random block experiment was conducted to test the effect of irrigation water quality on growth, productivity and sugar production of the crop. Results showed that the effluent meets the water quality standards for agricultural use (Ayers & Westcot 1985). In addition, according to the United States Department of Agriculture (USDA) (1954) both kinds of irrigation water were classified as C2S1. Crop growth behaved similar to that expected for the region and variety studied. Productivity variables were slightly above the expected values (145 t/ha sugar cane, 16.9% saccharose, 17.6% Brix grades). We did not find differences among plots irrigated with both water sources. Therefore, it can be concluded

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that the reuse of effluent for irrigation is viable for crop productivity, but other aspects like soil sodicity indicators must be further investigated.

Keywords: crop yield, irrigation, reuse, sugarcane, productivity, wastewater

1. Introduction

Only 0.003% of the Earth's total water is considered useful for human activities. Of this amount, developed countries use about 35% in agriculture, while developing countries use over 70% (FAO 2007) since they supply most of the world's food. The Food and Agriculture Organization (FAO) (2008) suggests that conservation measures need to be undertaken in the agricultural use of water in view of the expected increase in agricultural production in the next 50 years. Among the alternatives presented by the FAO (2008), rainwater harvesting, rain-fed agriculture, increased water productivity, and the reuse of wastewater are mentioned.

Over recent decades, relevance has been given to the comprehensive management of water, which has raised the possibility of reusing wastewater for irrigation in Latin America (for example in Argentina, Chile, Peru, Mexico), Europe (Germany), Africa (South Africa, Tunisia, Sudan), Asia (Israel, Kuwait, Saudi Arabia, India, China), and North America (Parreiras 2005). In Colombia the use of treated wastewater is not a common practice, given the low treatment levels and partial unawareness of the possible impacts upon the environment. According to Madera (2005) in Colombia only 8% of domestic wastewater is treated before discharge into natural water bodies, which has led to the indirect reuse of wastewater. Cali, Colombia's third most populated city has the Cañaveralejo Wastewater Treatment Plant (PTAR-C), which can operate under two modalities: Conventional Primary Treatment (CPT) and Chemically Enhanced Primary Treatment (CEPT).

Sugarcane cultivation is the main agricultural activity in the valley of the Cauca River. It has 208,254 ha planted with this crop, which represents 5% of the total area planted in Colombia (CENICAÑA 2010). The demand for irrigation water is ca. 300–400 mm/year (Torres et al. 2004), which represents considerable pressure on the surface and groundwater sources of the zone. The aim of this study was to assess the impact on the productivity of the sugarcane (variety CC-8592) irrigated with effluent from the PTAR-C under the climatic conditions of the Valle del Cauca region in southwest Colombia.

2. Materials and Methods

The study was carried out within the Cañaveralejo Wastewater Treatment Plant located in the north-eastern zone of the city of Cali on the left bank of the Cauca River (3° 28′ 7′′ N, 76° 28′ 40′′ W).

2.1. Experimental Design

The experimental design used for the research was of randomised complete blocks. Three blocks were established with nine furrows of sugarcane each. The furrows were 100 m long, 1.5 m wide, and there was an 18 m separation zone between blocks (Figures 1 and 2).

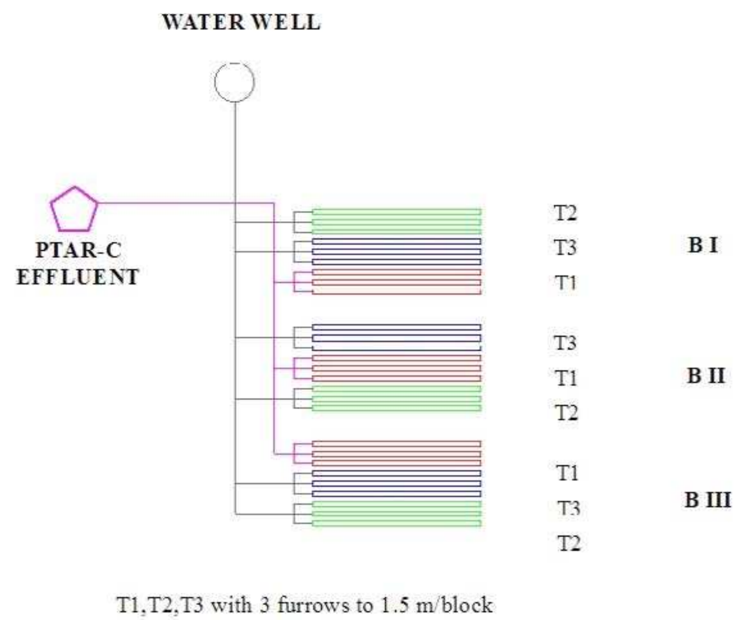

Figure 1: General layout of experimental set-up (not to scale) (B: Block. T 1,2,3: Treatments)

Figure 2: General view of the experimental set-up

The research factor was the quality of the irrigation water. The water sources were: groundwater and the effluent from the PTAR-C operating under CEPT. The experimental treatments were: T1: irrigation with effluent from PTAR-C, T2: irrigation with groundwater, and T3: irrigation with groundwater and the application of chemical fertilizers (urea, triple superphosphate and potassium chloride); the doses applied are shown in Table 1. Table 2 shows the initial soil nutritional status for each block. The research parameters were: sugarcane production (t/ha), saccharose (%), reducing sugars (%), and Brix grades (*Br). Table 3 presents the variables, sampling frequencies, and measurement techniques.

2.2. Soil Preparation and Irrigation Scheduling

The soil was an inceptisol with vertic properties (Vertic Endoaquept), silty clay texture and structure in angular blocks according to field description and the regional soil study (IGAC, 1980). The cultivation plots were subjected to levelling, ploughing, harrowing, and furrowing. The irrigation method was furrow irrigation using closed pipes in the conveyance system and gated pipes in the distribution system at field level. Irrigation scheduling was based on the daily water balance. Five irrigations (324 mm in total) were applied during the period of the crop's physiological development (August 2009–August 2010).

Table 1: Fertilization doses applied for T3 (0.045 ha block^{-1})

NUTRITIONAL REQUIREMENT (kg)				FERTILIZER (kg)		
Block	N	P2O5	K2O	Urea 46% N	Triple super-phosphate 46% P2O5	Potassium chloride 60% K2O
I	4.5	0.0	0.0	9.8	0.0	0.0
II	4.5	2.0	3.4	9.8	4.4	5.7
III	4.5	0.0	0.0	9.8	0.0	0.0
Total	**13.5**	**2.0**	**3.4**	**29.5**	**4.4**	**5.7**

Table 2: Chemical and macronutritional properties of soil and its cation ratios

Block	pH	Ca	K	Mg	Na	CEC_7	Ca/Mg	Mg/K	Ca+Mg/K	EC	ESP	OM	P-BrayII	N-NH_4	N-NO_3
	Und	cmol kg^{-1}								µmho cm^{-1}	%	gr kg^{-1}	mg kg^{-1}		
I	7.41	23.52	0.33	9.5	0.25	29.55	2.5	29	100	274	0.74	35.93	29.46	14.96	13.19
II	7.42	21.21	0.26	8.93	0.25	26.6	2.4	34	116	215	0.82	25.09	6.62	11.21	9.02
III	7.41	23.88	0.31	8.93	0.26	30.2	2.7	29	106	222	0.78	33.74	18.74	8.52	16.17
Mean	**7.41**	**22.87**	**0.30**	**9.12**	**0.25**	**28.78**	**2.5**	**31**	**107**	**237**	**0.78**	**31.59**	**18.27**	**11.56**	**12.79**

Table 3: Control and response variables

	PARAMETER	UNIT	SAMPLING	TECHNIQUE
Crop	Production	Tonne/ hectare	Weighing in field of the whole production	Weighing in field with Fair-banks scale 500-Kg capacity (precision: 0.25 Kg)
	Saccharose	%	Milling of 10 stalks per treatment and extraction of 100 ml for laboratory analysis	Liquid chromatography
	Reducing sugar	%		Liquid chromatography
	Brixgrades	%		Refractometry
Water	pH	-	A 1 liter sample of each water quality in each irrigation, taken at the outlet of the gated pipe	Potentiometer
	CEw	dSm^{-1}		Potentiometer
	Calcium	mEq L^{-1}		Spectrophotometry
	Magnesium	mEq L^{-1}		Spectrophotometry
	Sodium	mEq L^{-1}		Spectrophotometry
	Bicarbonates	mEq L^{-1}		Titration-metrics
	Chlorides	mEq L^{-1}		Titration-metrics
	Sulfates	mEq L^{-1}		Titration-metrics
	Nitrites	mg L^{-1}		Digestion titration
	Nitrates	mg L^{-1}		Digestion titration
	N- NH3	mg L^{-1}		Titration
	Phosphates (PO_4)	mg L^{-1}		Digestion titration

2.3. Data Analysis Techniques

Analysis of the results was carried out according to the experimental design (randomised complete blocks). The Anderson-Darling Test was used to check the normality of the data. One way ANOVA was applied to determine if there were differences between treatments (using MINITAB 15 software). The mathematical model assumed was:

$$Y_{ij} = \mu + A_i + B_j + E_{ij}$$

where Y_{ij} *is* the response variable; μ the population mean; Ai the effect of the ith treatment, B_j the effect of the j^{th} block, and E_{ij} the experimental error associated with the i^{th} treatment in the j^{th} block.

3. Results and Discussion

3.1. Irrigation Water Quality

Table 4 presents the characteristics of two irrigation water sources (groundwater and PTAR-C effluent). The values correspond to the average of the analyses performed on the five irrigations applied during the research. There were differences in the concentrations of ammonia nitrogen, total nitrogen, phosphates, and total phosphorus in relation to the PTAR-C effluent, which presented the highest values, even above the FAO reference values for irrigation given by Ayers & Westcot (1985). For nitrates, both the effluent and the groundwater were higher than the FAO reference values. The high nutrient values are characteristic of treated wastewater, and this is one of the potential benefits of reusing this water in irrigation. However, they also represent a potential risk to contaminating the groundwater, especially in light textured soils and in zones where irrigation methods are inefficient (for example, flood irrigation).

Table 4: Irrigation water quality (Average)

PARAMETER	UNIT	GROUND-WATER	S.D.	EFFLUENT	S.D.	RANGE*
pH	-	6.98	0.36	6.7	0.27	6.0 – 8.5
Electrical conductivity	dS m-1	0.45	0.11	0.6	0.05	0 – 3
Calcium	mEq L^{-1}	1.88	0.23	1.6	0.19	0 – 20
Magnesium	mEq L^{-1}	0.91	0.12	0.8	0.11	<5
Sodium	mEq L^{-1}	2.35	0.11	1.7	0.16	<3
Bicarbonate	mEq L^{-1}	3.57	0.91	3.1	0.77	<10
Chloride	mEq L^{-1}	1.21	0.71	1.0	0.81	0 – 30
Sulphate	mEq L^{-1}	0.79	0.96	1.0	0.95	0 – 20
SAR	-	1.99	0.04	1.5	0.13	0 – 15
Nitrites	mg L^{-1}	1.95	2.68	1.7	2.20	<5
Nitrates	mg L^{-1}	14.34	14.62	53.7	54.2	<5
N-NH3	mg L^{-1}	2.67	1.92	15.8	10.3	0 – 5
Total Nitrogen	mg L^{-1}	20.94	14.2	75.2	53.7	<30
Total phosphorus	mg L^{-1}	1.22	1.19	5.0	1.1	<2
Phosphates (PO_4)	mg L^{-1}	0.53	0.95	2.1	1.43	0 – 2

* *Range of normal values according to Ayers & Westcot (1985)*

The pH value of irrigation water is within the reference range of water quality for irrigation. The electrical conductivity, in both cases, is below the limit value (< 0.7 dSm^{-1}), which shows a low risk of salinisation. The values of sodium adsorption ratio (SAR) related to ECw values indicate a slight risk of sodicity in both cases (Ayers & Westcot 1985), which means a possible damage to the soil structure, due to the dispersion of soil aggregates by the Na ions. For this reason, the hazard of sodicity exists even though the Na content in the irrigation water did not reach levels considered as toxic (3 meq L^{-1}). Additionally, according to USDA (1954) both irrigation waters are classified as C2S1 – i.e., they are of medium salinity and thus suitable for the irrigation of crops moderately sensitive to salts, and low content of sodium with a certain riskiness of accumulation for sensitive crops like some fruits and avocado.

From the agronomic point of view, it was noted that the treated wastewater did not differ from the groundwater given that, according to the USDA (1954) and Ayers & Wescot (1985) both kinds of water have the same characteristics and are not potentially associated with any risk of soil salinisation. The hazard of sodicity is medium and could represent problems in soils with high contents of Na or Mg because it would enhance the dispersing effect of these ions (García et al. 2002). Soils in Colombia's sugarcane zone are generally of good fertility, but some zones present high contents of Mg and Na. The combined effect of the natural condition of these soils and the medium sodicity hazard of the effluent could increase the damage on the soil structure due to dispersing effect of the Na and Mg.

3.2. Yield of Sugarcane, Sugars, and Degrees Brix

Table 5 presents the results obtained from production (P), saccharose (S), reducing sugars (AR), and Brix grades (°Bx) for the experimental treatments. The Anderson-Darling Test showed that the data of all the variables followed the normal distribution (p >0.05). It can be observed that the mean production of sugarcane measured in tons of sugarcane per ha (TCH) was above the values expected in the region – i.e., production levels above the range of 110–130 TCH were obtained as reported by Cenicaña (2010).

Table 5: Average production response

BLOCK	T	P (t/ha)	S (%)	AR (%)	°Bx (%)
B1	T1	146.1	15.3	2.2	17.3
	T2	135.7	18.6	1.6	17.4
	T3	128.8	18.6	1.8	15.7
B2	T1	144.7	17.5	0.4	17.8
	T2	117.7	15.4	0.7	16.8
	T3	123.3	18.4	0.4	19.1
B3	T1	147.2	18.1	0.97	17.8
	T2	147.2	17.1	0.92	17.4
	T3	148.5	15.4	0.92	17.1
T1 mean		146	17	1.2	17.6
T2 mean		133.5	17	1.1	17.2
T3 mean		133.6	17.5	1	17.3

B: block; T: treatment; P: production of sugar cane; S: saccharose; AR: reducing sugars; °Bx: Brix grade.

If 120 TCH is taken as the regional average, treatment T1 increased sugarcane production by 21.6%. If the upper limit of the production range is taken as the reference, the increase in production was 12.3% (Figure 3). Analysis of variance indicated that there were no significant differences due to treatment (p = 0.197) or between blocks (p = 0.097).

According to these results, the application of effluent increased sugarcane production above the value obtained for T3 (i.e., the use of groundwater plus chemical fertilizers, such treatment being the common situation in the region), However, no statistically significant differences (p-value: 1.97) between treatments and among blocks (p-value: 0.97) were founded. Application of the effluent generated a similar production to that reported by the sugarcane sector and which has also an added advantage represented by the potential savings of chemical fertilizers that provide macronutrients (N, P, K).

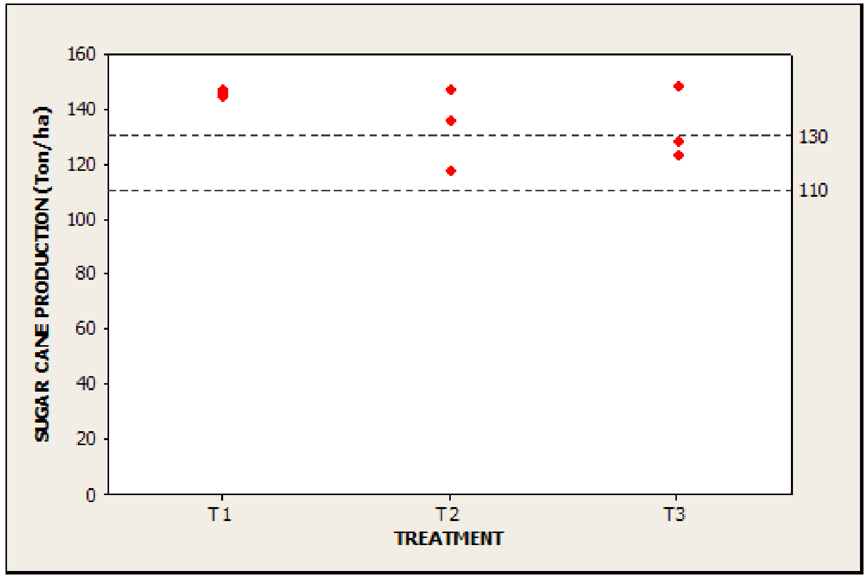

Figure 3: Sugarcane production per treatment

Also the mean saccharose content (%) of all the treatments is above the typical values for the valley of the Cauca River reported by Larrahondo (1995) – that is, values of 11.5–13.5%. The mean values for each treatment are similar to each other, but it should be noted that T1 (wastewater application) reported the lowest content of saccharose (3%) in spite of it having the highest sugarcane production. However, analysis of variance showed no significant differences among treatments (p = 0.945) or among blocks (p = 0.924) (Figure 4). From this analysis, it may be stated that wastewater application did not negatively affect the production of saccharose. The experimental values above the regional range may be explained by carrying out the experiment on soil that is not normally cultivated and which showed good fertility at the beginning of the study.

For the reducing sugars (RS), the mean value in all the treatments is within the range reported as normal for the region, which according to Larrahondo (1995) is between 1 and 5%. The mean values obtained are similar among treatments (Figure 4). Analysis of variance indicated that no differences existed between treatments (p=0.612), but found significant differences between blocks (p = 0.003).

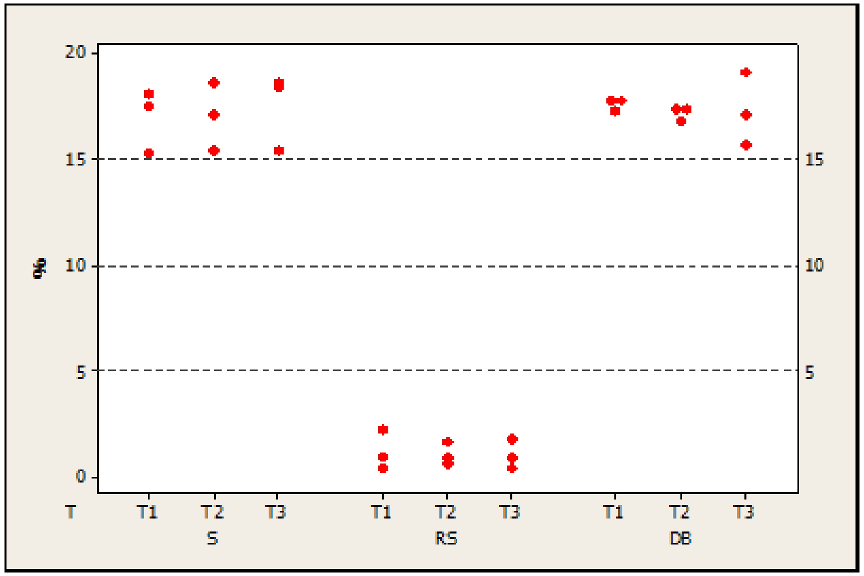

Figure 4: Saccharose (S), reducing sugars (RS), and Brix grades (BG) (%)

As for sugarcane production and saccharose, the mean values of Brix grades are above, in all the treatments, the range of common values for the valley of the Cauca River which according to Larrahondo (1995) are between 10 and 16%. The values obtained for this variable are similar, but T1 reports a slightly higher value than the other two treatments (Figure 4). The statistical analysis applied indicated that no significant differences existed between treatments (p = 0.874) or between blocks (p = 0.500). This analysis again confirms that reuse the PTAR-C effluent for irrigation of sugarcane (CC-8597) did not negatively affect the Brix grade.

Given that the nutritional status of the soil was homogeneous at the beginning of this research (Table 2), the results obtained in the four studied response variables show that sugarcane productivity was positively affected and the values are above those reported as desirable by the region's sugarcane production sector. Nevertheless, this may be associated with the fact that this was the soil's first production cycle for which higher production and productivity indicators are expected.

The productivity values found were similar to those reported by Silva (2008), who used the same water and soil and the same sugarcane variety, but in pots. This author obtained a yield of 133 t ha^{-1} of sugarcane. Regarding saccharose, the results of this current research are higher than those found by Silva (2008), who obtained 4.1% saccharose. Likewise, significant differences were not found in sugarcane production (TCH) or in saccharose (%) among the treatments studied. Productivity of the sugarcane variety was not affected, which shows that it is viable to use the PTAR-C effluent to irrigate sugarcane due to the higher concentrations of plant and soil nutrients.

4. Conclusion

Sugar cane production (TCH) was not affected by the application of the PTAR-C effluent as irrigation water. On the contrary, slightly higher values were obtained (133–145 t/ha) than the common range in the region (110–130 t/ha).

Reusing the effluent from the PTAR-C did not affect sugar production: values of saccharose, Brix grades, and reducing sugars remained within the ranges expected for the valley of the Cauca River, which are 11.5–13.5% for saccharose, 10–16% for Brix grade, and 1–5% for reducing sugars.

Given the productivity results obtained, it is concluded that the effluent from the PTAR-C supplied the crop's nutritional requirements (nitrogen, phosphorus, and potassium) in the first cultivation cycle.

The PTAR-C effluent represents a potential alternative for the irrigation of sugarcane under conditions of good soil fertility and low levels of Na and Mg to avoid possible dispersing effects of the soil aggregates. Additional studies should be conducted to assess the hazard of soil sodicity and groundwater contamination.

Finally, as a recommendation or lesson learned from this research, it is necessary to address research projects with a longer data collection period in order to identify eventual damage to the physical and/or chemical characteristics of the irrigated soil with the PTAR-C effluent.

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References

Ayers, R. S. and D.B. Westcot. 1985. "Water Quality for Agriculture." *Irrigation and Drainage Paper* No. 29, Rev. 1. Rome: Food and Agriculture Organization (FAO).

CENICAÑA (2010). "Informe Anual 2009" (in Spanish). CENICAÑA

FAO. 2007. *Water at a Glance – The Relationship between Water, Agriculture, Food Security and Poverty*. Rome: Food and Agriculture Organization.

FAO. 2008. *Agua para la Alimentación, Agua para la vida: Una Evaluación Exhaustiva de la Gestión del Agua en la Agricultura* (in Spanish). Colombo: Instituto Internacional del Manejo del Agua.

García, A., A. González, and A. Torrente. 2002. "*Propiedades químicas y físicas de los suelos magnésicos del Valle del Cauca (Colombia)*" (in Spanish). Suelos Ecuatoriales 30(2):74–141.

Instituto Geográfico Agustín Geográfico (IGAC). 1980. *Estudio Semi-detallado de Suelos del Valle Geográfico del Río Cauca* (in Spanish). Bogotá: IGAC.

Larrahondo, J. E. 1995. "*Calidad de la caña de azúcar*" (in Spanish). In El Cultivo de la Caña en la Zona Azucarera de Colombia, 337–354. Cali: Centro de Investigación de la Caña de Azúcar de Colombia.

Madera, C. 2005. "*Reuso de Agua Residual: Aspectos sobre la Calidad Necesitan Mayor Atención*" (in Spanish). Accessed May 2014.
http://pacificosur.rirh.net/legal_vista.php?id=5.

Parreiras, S. 2005. "*Tratamento de esgoto por disposição no solo*" (in Portuguese). Paper presented at "*O Curso sobre Tratamento de Esgoto por Disposição no Solo*", Belo Horizonte, May 30, 2005.

Silva, J. 2008. "*Reuso del Efluente de la Planta de Tratamiento de Aguas Residuales de Cañaveralejo PTAR-C en el Riego de Caña de Azúcar*" (in Spanish). MSc thesis. Universidad del Valle. Cali.

Torres, A. J. S., V. R. Cruz, and T. F. Villegas. 2004. "*Avances Técnicos para la Programación y el Manejo del Riego en Caña de Azúcar*" (in Spanish), 2nd ed. Technical Series No. 33. Cali: Centro de Investigación de la Caña de Azúcar de Colombia.

United States Department of Agriculture (USDA). 1954. "Diagnosis and Improvement of Saline and Alkali Soils." Regional Salinity Laboratory, Washington, D.C.

CASE 10

Accumulation of Heavy Metals in Cereal and Legume Crops through Sewage Water Irrigation and Phosphate Fertilisers (Pakistan)

G. Murtaza, M. Bilal Shakoor, and Nabeel Khan Niazi [1]

Abstract

Food crop irrigation with untreated sewage water is an increasingly common practice worldwide as well as in Pakistan, thus requiring management strategies for safe crop production on contaminated soils. In Pakistan, water availability has declined from 1,299 m^3 per capita in 1996-97 to 1,100 m^3 per capita in 2006 and is projected to fall below 700 m^3 per capita by 2025. Therefore, the irrigation of food crops with wastewater has become an important practice. A field study was conducted to examine the phyto-availability of three heavy metals (cadmium (Cd), copper (Cu), and zinc (Zn)) in two cereal (wheat, maize) and legume (chickpea, mung bean) crops in response to the application of sewage water or phosphatic fertiliser over two successive years. Five fertiliser treatments, i.e. control, recommended nitrogen (N) applied alone and in combination with three levels of phosphorus (P): half, full and 1.5 times the recommended P designated as N0P0, N1P0, N1P0.5, N1P1.0, and N1P1.5, respectively. Tissue concentrations of Cd, Cu, Zn, and P were determined in various plant parts (root, straw, and grains). While maximum biomass production was obtained with the application of P at half the recommended dose, the concentrations of heavy metals

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in crops generally decreased with increasing P levels. Tissue metal concentrations increased with the application of N alone. Translocation and accumulation of Zn and Cu were consistently higher than Cd. The pattern of Cd accumulation differed among plant species – relatively more Cd being accumulated by dicots than monocots, especially in their grains. The order of Cd accumulation in grains was maize > chickpea > mung bean > wheat. Mung bean and chickpea straws also had higher tissue Cd concentration above permissible limits. The two legume species behaved similarly, while cereal species differed from each other in their Cd accumulation. Metal ion concentrations were markedly higher in roots followed by straw and grains. Increasing soil-applied P also increased the extractable metal and P concentrations in the post-harvest soil. Despite a considerable addition of metals by P fertiliser, all levels of applied P effectively decreased metal phyto-availability in sewage water-irrigated soils, and applying half of the recommended dose of P fertiliser was the most feasible solution for curtailing plant metal uptake from soils. These findings may have wide applications for the safer crop production of monocot species when irrigating crops with sewage water containing heavy metals.

Keywords: city sewage, cereal, legume, metal uptake, phosphate fertiliser

1. Introduction

Over the past few decades many societies have experienced increased economic development driven by large-scale urbanisation and industrialisation, which has undoubtedly increased the demand for metals and consequently led to intensive anthropogenic environmental emissions. In particular, the contamination of soils with toxic metals has become a matter of worldwide agricultural and environmental concern affecting the health of crops, livestock and humans (Huang et al. 2012).

Both natural (weathering of parent material, volcanism) and anthropogenic sources have resulted in the widespread release of heavy metals in the soil and water environments (Purushotham et al. 2013). The agricultural use of pesticides, herbicides, fertilisers, municipal solid wastes, sewage sludge, irrigation with wastewater, burning of fossil fuels, smelting/mining activities, automobiles, incineration of waste, and waste disposal are the major anthropogenic causes of soil contamination with heavy metals (Murtaza et al. 2011). Cadmium is a non-essential element, which is of particular concern as a food chain contaminant owing to its greater solubility and bioavailability, as well as its inherent high toxicity, even at low concentrations, to both plants and human beings (Sarwar et al. 2010). In comparison, while at low concentrations Zn and Cu are both important essential micronutrients for plants, when present at higher concentrations, they also become important toxic pollutants. Due to their chemical similarities, Cd, Cu, and Zn interact in soil-plant systems and can affect the bioavailability of each other (Kim et al. 2010).

In plants, metals present at toxic levels disturb several physiological, biochemical and metabolic processes including photosynthesis and respiration (Ekmekçi et al. 2008), mineral nutrient uptake, translocation and metabolism (Sarwar et al. 2010), cell elongation and the activity of several enzymes (Gopal and Rizvi 2008). Consequently, plants have developed several strategies to partition and translocate metals into different plant parts (i.e. root, shoot and grain) in different proportions. Since cereal and legume crops differ in their root morphology, root density, genetic makeup, and tendency for metal uptake, translocation and accumulation (Nuruzzaman et al. 2006), studying the differing responses to the metal toxicity of these two broad crop classes is of great importance.

Nitrogen and phosphate fertilisers, besides providing plant nutrients and increasing food production, also impact soil pH, ionic strength, surface charge, complex formation, rhizosphere composition and soil microbial activity (Zhang et al. 2010). Changes in soil and crop management for both cereal and legumes in order to obtain high yields can also inadvertently influence the phyto-availability of Cd, Cu and Zn and hence possible entry in the food chain (Grant 2011).

In Pakistan, di-ammonium phosphate (DAP) and urea are the two main chemical inputs commonly used for supplementing the P and N demand of crops. Hence their effect on metal behaviour, bioavailability and accumulation in crop species grown on contaminated soils is of particular significance for safe crop production (McGowen et al. 2001). Legume and cereal crops are both important and ubiquitous sources of food for humans and feed and fodder for animals. However, the increased use of sewage water for irrigation has resulted in metal contamination in many agricultural soils, which is of grave concern for field crop cultivation. Thus, this field study was specifically conducted to assess the phyto-availability and accumulation of Cd, Cu and Zn in cereal and legume crops as influenced by P fertiliser application and irrigation with city sewage water.

2. Materials and Methods

2.1 Experimental Site

The study area was situated in a suburban area of Faisalabad, Pakistan, where untreated city sewage water has been used to irrigate cereals, millets, fodders and vegetables for more than 30 years.

2.2 Cultivation of Crops

A two-year field experiment was conducted during 2006-08 to investigate the uptake of metals in different monocot (wheat, maize) and dicot (chickpea, mung bean) plants irrigated with wastewater or supplemented with phosphatic fertilisers. The research area was divided into four plots (18.2 × 13.6 m^2) where wheat (*Triticum aestivum* L. cvs. Bhakkar-2002 and AS-2002), chickpea (*Cicer arietinum* L. cvs. Bittal-98 and Punjab-2000), maize (*Zea mays* L. cvs. Sahiwal-2002 and Monsanto 6525) and mung bean (*Vigna radiata* L. cvs. NIAB-92 and NIAB-2006) were sown in separate plots according to their respective growing seasons during 2006-07 and 2007-08.

The experiment used a split plot design with three replicates on an area of land which had long been irrigated with city sewage at the Land Utilisation Farm, Uchkera, University of Agriculture, Faisalabad, Pakistan. Seeds were sown at rates of 125, 60, 40 and 25 kg ha^{-1} for wheat, chickpea, maize and mung bean, respectively. The physico-chemical characteristics of the soil (Table 1) were determined using standard methods.

Table 1: Physiochemical Properties of the Soil Used in this Study

Soil Parameter	Value
Sand (%)	65
Silt (%)	25
Clay (%)	10
Textural class	Sandy loam
pH_s	7.65
ECe (dS m^{-1})	1.9
OM (%)	1.2
$CaCO_3$ (%)	0.9
HCO_3- (mmolc L^{-1})	1.3
Cl^- (mmolc L^{-1})	5.0
Ca^{2+}+Mg^2+ (mmolc L^{-1})	2.1
Na^+ (mmolc L^{-1})	16.0
K^+ (mmolc L^{-1})	0.38
SAR (mmol $L^{-1})^{1/2}$	15.70
AB-DTPA extractable	
Cd (mg kg^{-1})	0.42
Zn (mg kg^{-1})	6.66
Cu (mg kg^{-1})	1.57
P (mg kg^{-1})	18
Total metals (HNO_3 and $HClO_4$; 1:4)	
Cd (mg kg^{-1})	5.8
Zn (mg kg^{-1})	8.64
Cu (mg kg^{-1})	69.6

EC_e, Electrical conductivity of saturated soil paste extract; OM, organic matter; SAR, Sodium adsorption ratio

2.3 Fertiliser Treatments

Fertiliser rates were not based on soil P test values, but instead common recommendations for NP fertiliser of normal soils were followed. Urea (46% N) and DAP (46% P2O5 and 18% N) were used as a source of N and P (Table 2) and metal input through DAP is given in Table 3.

2.4 Sewage Water

The chemical properties of city sewage used for irrigation are given in Table 4. Total metal added to the soil through sewage irrigation for crops is given in Table 5. The total volume of city sewage delivered to each experimental unit was calculated in the open channel using the Manning equation (Akgiray 2005):

$$Q = A/n \times R^{2/3} \times S^{1/2}$$

where Q = Discharge (m^3 s^{-1}); A = Cross-sectional area (m^2); n = Manning's Roughness Coefficient (0.08); R = Hydraulic Radius (m) and S = Slope of the channel (m/m)

Table 2: Fertiliser Treatments Applied to Each Crop

Treatment (F)	N AND P_2O_5 (kg ha^{-1}) Wheat		Chickpea	Maize	Mung bean
Control	N_0P_0	0-0	0-0	0-0	0-0
Recommended N+0.0 P	N_1P_0	113-0	23-0	120-0	23-0
Recommended N+0.5 P	$N_1P_{0.5}$	113-57	23-28	120-57	23-28
Recommended N+1.0 P	$N_1P_{1.0}$	113-113	23-58	120-113	23-58
Recommended N+1.5 P	$N_1P_{1.5}$	113-170	23-85	120-170	23-85

Table 3: Total Metal Input (mg ha^{-1}) through DAP Fertiliser Amendment

Crops	Treatments	METAL INPUTS (mg ha^{-1}) Cd (16 mg kg^{-1} DAP)	Zn (313 mg kg^{-1} DAP)	Cu (42.6 mg kg^{-1} DAP)
Wheat and Maize	$N_1P_{0.5}$	1993	38671	5182
	$N_1P_{1.0}$	3986	77343	10365
	$N_1P_{1.5}$	5980	115616	15548
Chickpea and Mung bean	$N_1P_{0.5}$	956	19136	2392
	$N_1P_{1.0}$	2033	38272	5182
	$N_1P_{1.5}$	2974	57409	7853

Contamination with pathogens (bacteria and viruses) is mostly associated with domestic sewage. It is established that coliform bacteria and helminth eggs should be ≤ 10 and ≤ 0.01 mL^{-1}, respectively. According to Ensink et al. (2004), for Faisalabad city sewage, faecal coliform was 6.3×10^7 and $> 1 \times 10^8$, and helminth eggs were 100 and 763, respectively, and the sewage is a mixture of domestic and industrial discharge, which has not been characterised for its biological contamination.

2.5 Plant Harvesting and Analysis

Crop plants were harvested at reproductive maturity. The concentrations of Cd, Cu and Zn were determined via atomic absorption spectrophotometer (Thermo Electron AA, Solar-Series, Waltham, USA) following a di-acid (HNO_3+$HClO_4$; 3:1) digestion of samples in triplicate (AOAC 1920), and phosphorus concentrations were determined using a UV-visible spectrophotometer (Thermo Electron, Waltham, USA), standardised with a series of standard solutions supplied by the manufacturer.

Table 4: Selected Chemical Characteristics of Untreated Sewage Water Used for Crop Irrigation during this Study

Parameter	Range	Mean*	SD**
pH	7.3 - 7.9	7.47	0.17
EC (dS m^{-1})	2.64 - 3.13	2.95	0.18
TSS (mmolc L^{-1})	26.4 - 31.2	29.50	0.03
BOD (mg L^{-1})	4.0 - 988	-	-
COD (mg L^{-1})	42 - 2676	-	-
Na^+ (mmolc L^{-1})	16.5 - 27	21.75	3.45
K^+ (mmolc L^{-1})	0.3 - 0.8	0.56	0.15
Ca^{2+}+Mg^{2+} (mmolc L^{-1})	3.2 - 7.4	6.15	1.26
HCO_3- (mmolc L^{-1})	7.0 - 10.0	8.17	0.99
Cl^- (mmolc L^{-1})	5.7 - 13.0	11.0	2.39
SO_4^{2-} (mmolc L^{-1})	7.4 - 19	11.16	3.98
SAR (mmol L^{-1})$^{1/2}$	8.82 - 21.30	12.78	3.80
RSC (mmolc L^{-1})	0.6 - 6.80	2.05	1.90
Cd (mg L^{-1})	Traces - 0.002	0.001	0.01
Cr (mg L^{-1})	0.05 - 1.62	0.715	0.55
Cu (mg L^{-1})	0.001 - 0.026	0.01	0.01
Ni (mg L^{-1})	0.03 - 1.25	0.471	0.38
Pb (mg L^{-1})	0.04 - 0.70	0.313	0.06
Zn (mg L^{-1})	0.01 - 0.072	0.033	0.02

** (Average of six observations, n=6) ** SD= Standard deviation*
EC, Electrical conductivity; TSS, Total Suspended Solids; SAR, Sodium adsorption ratio; RSC, Residual sodium carbonate; BOD, Biological oxygen demand; COD, Chemical oxygen demand.

Table 5: Total Metal Input through Wastewater Irrigation

Crops	Metal addition through wastewater (mg ha^{-1} $Season^{-1}$)		
	Cd (0.002 mg L^{-1})	Zn (0.033 mg L^{-1})	Cu (0.01 mg L^{-1})
Wheat and Maize	914	21031	4571
Mung bean and Chickpea	609	14020	3047

2.6 Statistical Analysis

Statistical analysis was carried out using the "Statistix 8.1" statistical package using the least significant difference (LSD) test to compare the means.

3. Results

3.1 Plant Biomass Production

Both crop species and fertiliser treatments had a significant positive ($p < 0.05$) effect on grain and straw yields for wheat (Table 6). Relative to the control (N_0P_0), all levels of P increased wheat yield, while the application of N alone decreased grain yield (4,937 kg ha^{-1}). The highest grain (5,661 kg ha^{-1}) and straw (7,801 kg ha^{-1}) yields were recorded for crop species BKR-02.

For maize, treatments had a significant ($p < 0.05$) influence on both grain and straw yields. The highest grain (3,031 kg ha^{-1}) and straw (8,370 kg ha^{-1}) yields were obtained with treatment N1P1.5 and the lowest yield was obtained in the control (N_0P_0).

For mung bean, both fertiliser treatments and crop species positively ($p < 0.05$) increased grain yield (Table 6) with NIAB-06 producing a 5.2% higher grain yield (2,048 kg ha^{-1}) than NIAB-92 (1,948 kg ha^{-1}). All P treatments increased grain yield.

For chickpea, fertilisers, crop species and their interactions had a positive ($p < 0.05$) influence on grain and straw yields (Table 6). Bital-98 produced higher grain (2,243 kg ha^{-1}) and straw (4,037 kg ha^{-1}) yields than P-2000.

3.2 Plant Metal Concentrations

Increasing rates of P combined with the recommended N dose (113 kg ha^{-1}) decreased tissue metal concentrations. The lowest metals were accumulated in wheat variety AS-02, while the maize hybrid M-6525 accumulated more Cd and less Cu in all plant parts than S-02.

Metal concentrations in the tissues of legumes significantly ($p < 0.05$) decreased with increasing levels of P. Thus the highest concentrations of Zn in plant tissue were recorded in the control and N1P0 for chickpea and mung bean, respectively. NIAB-92 (mung bean) accumulated higher amounts of metal compared with NIAB-06 (Tables 7, 8, 9) accumulating 2.6, 11.3 and 21.0% more Zn in the grain, straw and root, respectively than NIAB-06.

3.3 Plant P Concentrations

Differences in P contents in wheat and maize varied significantly ($p < 0.05$) with crop species, fertiliser treatments and their interactions (Table 10). Relative to control, and to adding N alone, the application of P fertiliser significantly increased plant P contents. With the exception of P straw, crop species generally differed significantly in their P contents. Relative to the control (N_0P_0), the application of N alone (N1P0) enhanced P tissue content in maize plants but decreased P tissue content in wheat plants.

The effect of fertiliser treatments, crop species and their interaction were all significant ($p < 0.05$) on P tissue contents in both legume species (Table 10). Relative to the control, the application of N alone (N1P0) also significantly improved P tissue content in both legume crops.

3.4 Translocation of Metals

The translocation factors (TF) of all measured metals (Cd, Cu and Zn) was highest under treatment N1P0 and decreased with increasing P levels (Table 11) for all plant species. The average TF decreased in the order mung bean (1.77) > chickpea (1.20) > wheat (1.14) > maize (1.03).

3.5 Post-Harvest Soil Analysis

After harvesting all of the crops, soil analysis revealed that the application of P had resulted in increases in the AB-DTPA extractable metal content (Cd, Cu and Zn) and P in soil corresponding to the level

Table 6: Effect of fertiliser treatments and crop species on biomass production (kg ha^{-1}) of cereal and legume crops

	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
Treatment	BKR-02	AS-02	S-02	M-6520	Bital-98	P-2000	NIAB-92	NIAB-06
Grains								
N_0P_0	5575±121^{bc}	5010±146de	2358±34^{g}	2936±25^{cd}	2073±23^{c}	1607±35^{f}	1863±29^{efg}	1924±43^{def}
N_1P_0	5090±58de	4784±23^{e}	2491±57^{f}	3016±13^{c}	1926±35^{d}	1541±48^{f}	1757±28^{g}	1773±21^{fg}
$N_1P_{0.5}$	6007±182^{a}	5236±105^{cd}	2631±40^{e}	3162±37^{b}	2445±13^{a}	1754±23^{e}	2046±39^{bcd}	218±57^{ab}
$N_1P_{1.0}$	5914±133^{ab}	5150±218^{cde}	2678±52de	3221±62^{ab}	2365±35^{a}	2192±40^{b}	2071±31^{abc}	2211±40^{a}
$N_1P_{1.5}$	5721±53^{ab}	5209±37^{cd}	2764±15^{cd}	3299±15^{a}	2405±35^{a}	2073±46^{c}	2004±49^{cde}	2149±101^{ab}
Straw								
N_0P_0	7382±207^{b}	5887±82^{c}	8176±23^{cd}	8067±21^{d}	4385±115^{b}	3960±27^{c}	1985±185^{a}	2144±25^{a}
N_1P_0	7203±188^{b}	6113±185^{c}	8202±46^{bcd}	8209±80^{bcd}	4837±53^{a}	4119±66^{bc}	2360±163^{a}	2213±170^{a}
$N_1P_{0.5}$	8479±67^{a}	7057±120^{b}	8288±43^{abc}	8304±14^{abc}	3973±242^{c}	3455±56^{d}	2272±183^{a}	2313±59^{a}
$N_1P_{1.0}$	8372±150^{a}	6146±202^{c}	8332±30^{abc}	8370±50^{a}	3907±144^{c}	3255±47^{c}	2140±109^{a}	2249±71^{a}
$N_1P_{1.5}$	7568±92^{b}	5954±185^{c}	8388±67^{a}	8352±70^{ab}	3083±157^{d}	3123±76^{d}	2168±55^{a}	2296±102^{a}

Values are means ± standard error (n=3); LSD values for grain and straw of wheat; 145, 201, maize; 62, 53, chickpea; 82.7, 135 and mung bean; 104, 245, respectively.

Table 7: Effect of fertiliser treatments and crop species on concentration of Cd (mg kg^{-1}) in root, straw and grains of cereal and legume crops

	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
Treatment	**BKR-02**	**AS-02**	**S-02**	**M-6520**	**Bital-98**	**P-2000**	**NIAB-92**	**NIAB-06**
Grains								
N_0P_0	0.046±0.003^{cd}	0.042±0.003^{cd}	0.110±0.006^{de}	0.110±0.013^{a}	0.140±0.006^{ab}	0.130±0.015^{abc}	0.041±0.006^{c}	0.014±0.025^{a}
N_1P_0	0.054±0.003^{bc}	0.063±0.003^{cd}	0.140±0.015^{cd}	0.140±0.023^{a}	0.130±0.003^{ab}	0.150±0.012^{ab}	0.073±0.015^{bc}	0.050±0.012^{c}
$N_1P_{0.5}$	0.056±0.000^{b}	0.085±0.003^{a}	0.150±0.009^{cde}	0.150±0.011^{ab}	0.150±0.012^{ab}	0.160±0.026^{a}	0.143±0.012^{a}	0.053±0.009^{c}
$N_1P_{1.0}$	0.064±0.003^{b}	0.080±0.006^{a}	0.140±0.020^{cde}	0.140±0.014^{ab}	0.150±0.007^{ab}	0.120±0.007^{abc}	0.133±0.007^{a}	0.139±0.027^{ab}
$N_1P_{1.5}$	0.035±0.003^{d}	0.038±0.002^{d}	0.090±0.009^{e}	0.090±0.027^{bc}	0.100±0.003^{c}	0.110±0.015^{bc}	0.133±0.003^{a}	0.132±0.006^{a}
Straw								
N_0P_0	0.195±0.009^{bc}	0.169±0.010^{cd}	0.280±0.006^{abc}	0.260±0.016^{bc}	0.220±0.006^{c}	0.400±0.006^{b}	0.895±0.012^{bc}	0.760±0.032^{c}
N_1P_0	0.255±0.009^{abc}	0.245±0.003^{ab}	0.260±0.015^{a}	0.260±0.013^{bc}	0.250±0.003^{c}	0.260±0.006^{b}	0.911±0.096^{bc}	0.875±0.062^{c}
$N_1P_{0.5}$	0.289±0.015^{abc}	0.235±0.012^{a}	0.220±0.009^{cd}	0.330±0.010^{bc}	0.160±0.012^{a}	0.180±0.006^{a}	1.240±0.080^{a}	1.105±0.058^{ab}
$N_1P_{1.0}$	0.263±0.012^{a}	0.271±0.018^{ab}	0.220±0.020^{cd}	0.290±0.037^{ab}	0.120±0.007^{a}	0.120±0.012^{a}	0.425±0.069^{d}	0.457±0.068^{d}
$N_1P_{1.5}$	0.244±0.020^{d}	0.157±0.044^{abc}	0.191±0.009^{d}	0.270±0.010^{bc}	0.100±0.003^{a}	0.100±0.012^{a}	0.320±0.075^{d}	0.326±0.061^{d}
Root								
N_0P_0	0.247±0.018^{def}	0.208±0.015^{ef}	0.770±0.028^{ab}	0.870±0.076^{a}	0.610±0.074^{g}	0.420±0.103^{fg}	0.608±0.053^{c}	0.548±0.064^{c}
N_1P_0	0.212±0.018^{f}	0.273±0.005^{cde}	0.570±0.007^{bc}	0.890±0.151^{a}	0.720±0.062^{ef}	0.450±0.135^{de}	1.086±0.066^{ab}	0.730±0.080^{c}
$N_1P_{0.5}$	0.286±0.031^{c}	0.275±0.017^{cd}	0.500±0.012^{ab}	0.730±0.073^{ab}	0.450±0.044^{d}	0.410±0.090^{c}	0.839±0.038^{bc}	0.881±0.031^{bc}
$N_1P_{1.0}$	0.631±0.024^{a}	0.176±0.026^{g}	4.460±0.018^{c}	0.700±0.135^{abc}	0.390±0.027^{bc}	0.390±0.068^{ab}	1.406±0.194^{bc}	0.804±0.232^{c}
$N_1P_{1.5}$	0.379±0.041^{b}	0.139±0.066^{h}	0.460±0.005^{c}	0.550±0.074^{bc}	0.250±0.021^{a}	0.250±0.023^{abc}	0.850±0.192^{a}	0.542±0.065^{bc}

Values are means ± standard error (n=3); LSD values for grain, straw and root of wheat; 0.005, 0.02, 0.03 maize; 0.02, 0.05, 0.07, Chickpea; 0.02, 0.035, 0.09 and mung bean; 0.009, 0.20, 0.25, respectively.

Table 8: Effect of fertiliser treatments and crop species on concentrations of Zn (mg kg^{-1}) in root, straw and grains of cereal and legume crops

	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
Treatment	**BKR-02**	**AS-02**	**S-02**	**M-6520**	**Bital-98**	**P-2000**	**NIAB-92**	**NIAB-06**
Grains								
N_0P_0	40.90±0.59^{ab}	45.10±0.50^{e}	31.80±0.79^{a}	27.70±1.24^{bc}	39.30±1.18^{a}	35.90±0.35^{ab}	33.60±0.74^{a}	32.90±0.66^{bcd}
N_1P_0	42.00±0.53^{a}	43.80±1.03^{de}	34.10±1.13^{ab}	26.60±0.76^{bc}	38.10±0.87^{a}	36.90±0.98^{ab}	36.60±0.97^{abc}	34.00±0.89^{ab}
$N_1P_{0.5}$	39.60±0.67^{bc}	39.30±0.47^{bcd}	25.50±2.09^{cd}	25.30±1.54^{cde}	36.50±0.97^{ab}	36.90±1.00^{bc}	32.10±1.34^{bcd}	31.40±0.46^{b-e}
$N_1P_{1.0}$	37.80±0.47^{cde}	36.80±0.25^{cde}	23.00±2.03^{cde}	24.40±0.45^{cde}	34.30±1.32^{bc}	34.10±1.21^{cd}	31.30±0.88^{cde}	29.40±1.50^{ef}
$N_1P_{1.5}$	32.20±0.95^{e}	34.50±0.38^{cde}	20.30±2.22^{e}	21.30±0.46^{de}	29.70±0.64^{d}	32.40±0.53^{d}	30.50±0.32^{de}	26.80±0.89^{f}
Straw								
N_0P_0	24.80±1.97^{fg}	23.90±0.89^{g}	28.60±1.03^{a}	27.10±0.68^{bc}	21.90±0.72^{e}	25.50±1.03^{de}	31.70±2.41^{a}	26.90±1.17^{a}
N_1P_0	28.90±1.30^{a}	25.40±0.30^{b}	30.80±0.84^{ab}	25.90±0.94^{c}	21.30±0.52^{e}	23.50±0.45^{cd}	32.60±1.19^{a}	27.90±1.37^{a}
$N_1P_{0.5}$	24.20±0.78^{bc}	20.30±0.79^{def}	21.40±0.47^{de}	22.80±1.09^{d}	24.70±0.75^{cd}	30.20±0.45^{a}	32.10±2.30^{a}	29.50±1.30^{a}
$N_1P_{1.0}$	22.50±0.29^{bcd}	15.90±0.84^{g}	20.30±0.67^{de}	20.30±0.67^{de}	25.50±0.92^{cd}	28.60±1.00^{ab}	31.50±1.74^{a}	27.70±2.49^{a}
$N_1P_{1.5}$	21.10±0.78^{bcd}	13.70±0.42^{ef}	19.10±1.03^{e}	19.20±0.67^{e}	26.50±0.65^{bc}	28.50±0.58^{ab}	33.30±0.96^{a}	33.30±1.35^{a}
Root								
N_0P_0	46.30±1.70^{ab}	39.20±1.45^{cd}	22.90±1.01^{bc}	21.60±0.98^{c}	34.80±0.99^{ab}	35.10±2.71^{a}	22.70±3.17^{ab}	18.80±0.62^{ab}
N_1P_0	46.30±1.15^{ab}	41.30±1.23^{bcd}	25.50±0.78^{ab}	22.80±0.49^{bc}	33.20±1.31^{ab}	30.30±0.84^{bc}	20.70±0.92^{ab}	18.40±1.93^{ab}
$N_1P_{0.5}$	46.90±2.22^{ab}	49.00±4.74^{a}	26.30±0.23^{a}	25.40±1.14^{ab}	32.00±0.46^{ab}	27.20±0.51^{cde}	23.70±3.02^{a}	17.10±1.67^{b}
$N_1P_{1.0}$	40.10±0.92^{cd}	42.40±0.72^{bc}	24.80±0.52^{ab}	24.90±0.95^{ab}	26.80±1.98^{cde}	24.40±1.12^{de}	23.20±2.34^{ab}	19.10±1.71^{ab}
$N_1P_{1.5}$	35.70±1.63^{de}	31.90±1.81^{e}	23.80±0.47^{abc}	24.60±1.27^{ab}	27.20±0.79^{cd}	22.90±1.32^{e}	22.20±2.03^{ab}	18.50±0.95^{ab}

Values are means ± standard error (n=3); LSD values for grain, straw and root of wheat; 2.2, 1.6, 2.1, maize; 1.92, 1.45, 1.72, Chickpea; 1.34, 1.45, 1.54 and mung bean; 1.52, 1.80, 1.62, respectively.

Table 9: Effect of fertiliser treatments and crop species on concentrations of Cu (mg kg^{-1}) in root, straw and grains of cereal and legume crops

	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
Treatment	**BKR-02**	**AS-02**	**S-02**	**M-6520**	**Bital-98**	**P-2000**	**NIAB-92**	**NIAB-06**
Grains								
N_0P_0	4.60±0.10^{b}	4.70±0.15^{a}	2.46±0.09^{a}	1.91±0.09^{b}	5.40±0.77^{a}	5.10±0.16^{a}	9.44±0.19^{c}	5.84±0.24^{a}
N_1P_0	4.70±0.23^{b}	5.30±0.12^{b}	2.39±0.06^{a}	1.86±0.07^{b}	5.40±0.70^{a}	5.10±0.15^{a}	9.34±0.35^{c}	5.59±0.32^{a}
$N_1P_{0.5}$	4.20±0.09^{cd}	4.40±0.06^{bc}	2.36±0.07^{a}	1.68±0.09^{bc}	4.50±0.20^{ab}	4.40±0.16^{ab}	8.50±0.15^{c}	5.77±0.51^{ab}
$N_1P_{1.0}$	4.10±0.12^{cde}	4.00±0.15^{cde}	1.31±0.17^{d}	1.54±0.07^{cd}	3.60±0.23^{bc}	3.80±0.18^{bc}	7.83±0.47^{c}	5.57±0.22^{b}
$N_1P_{1.5}$	3.80±0.12^{de}	3.70±0.09^{e}	1.09±0.09^{e}	1.33±0.02^{d}	2.40±0.62^{c}	2.70±0.23^{c}	7.28±0.22^{c}	5.65±0.26^{b}
Straw								
N_0P_0	5.40±0.23^{b}	5.20±0.18^{b}	4.63±0.19^{a}	3.64±0.50^{c}	4.73±0.41^{a}	3.52±0.57^{a}	10.40±0.15^{ab}	9.96±0.58^{abc}
N_1P_0	6.40±0.55^{ab}	5.40±0.50^{b}	4.28±0.21^{abc}	3.54±0.31^{c}	4.23±0.19^{a}	3.58±0.10^{a}	9.19±0.42^{bc}	9.23±0.88^{bc}
$N_1P_{0.5}$	6.40±0.18^{ab}	7.10±0.64^{a}	4.56±0.17^{ab}	3.70±0.23^{c}	3.87±0.54^{a}	3.46±0.10^{a}	11.54±0.32^{a}	9.45±0.90^{abc}
$N_1P_{1.0}$	6.20±0.38^{ab}	6.03±0.18^{ab}	4.29±0.20^{abc}	3.71±0.20^{c}	3.97±0.41^{a}	3.34±0.11^{a}	10.41±0.43^{ab}	8.97±0.82^{bc}
$N_1P_{1.5}$	6.10±0.26^{ab}	5.90±0.44^{ab}	4.01±0.20^{abc}	3.75±0.15^{bc}	4.27±0.27^{a}	3.22±0.02^{a}	10.31±0.35^{ab}	8.03±0.84^{c}
Root								
N_0P_0	14.10±0.29^{ab}	10.10±0.32^{c}	14.08±0.78^{a}	12.23±1.09^{abc}	11.30±1.92^{ab}	12.40±0.74^{ab}	11.79±0.09^{ab}	11.93±0.39^{ab}
N_1P_0	14.80±0.62^{a}	12.30±1.16^{bc}	12.23±0.34^{bcd}	11.83±0.55^{abc}	11.80±1.07^{ab}	13.10±0.90^{ab}	12.59±0.32^{a}	11.78±0.70^{ab}
$N_1P_{0.5}$	11.10±1.45^{c}	11.00±1.60^{c}	12.71±0.44^{ab}	12.90±1.44^{a-d}	10.60±1.33^{abc}	11.70±0.23^{b}	11.89±0.67^{b}	11.22±1.35^{ab}
$N_1P_{1.0}$	11.00±0.85^{c}	10.10±0.62^{c}	10.39±0.87^{cd}	9.53±1.27^{bcd}	9.10±0.45^{bc}	11.20±0.62^{ab}	10.86±0.73^{ab}	10.53±0.66^{ab}
$N_1P_{1.5}$	9.20±0.32^{c}	9.00±0.40^{c}	9.20±0.28^{d}	8.68±1.52^{d}	9.20±1.33^{bc}	7.20±1.16^{c}	10.47±0.32^{a}	10.31±0.66^{ab}

Values are means ± standard error (n=3); LSD values of grain, straw and root of wheat; 0.15, 0.5, 1.2, maize; 0.22, 0.58, 1.35, chickpea; 0.29, 0.43, 1.07 and mung bean; 1.85, 1.15, 1.47, respectively.

Table 10: Effect of fertiliser treatments and crop species on concentrations of P (mg kg^{-1}) in root, straw and grains of cereal and legume crops

	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
Treatment	**BKR-02**	**AS-02**	**S-02**	**M-6520**	**Bital-98**	**P-2000**	**NIAB-92**	**NIAB-06**
Grains								
N_0P_0	3554±17^{b}	3484±17^{b}	3794±31^{e}	4091±83^{c}	3890±17^{d}	4343±06^{f}	4691±13^{e}	4588±14^{f}
N_1P_0	3548±36^{b}	3438±34^{b}	3785±23^{e}	4074±21^{bc}	4064±24^{c}	4566±33^{e}	4858±26^{d}	4662±23^{e}
$N_1P_{0.5}$	3904±40^{a}	3954±55^{a}	3853±47de	4224±42^{ab}	4351±39^{b}	4869±22^{d}	5019±17^{a}	4878±12^{cd}
$N_1P_{1.0}$	3881±36^{a}	3821±43^{a}	3959±55^{cd}	4319±50^{a}	4525±20^{a}	5053±22^{c}	5031±16^{a}	4917±13^{bc}
$N_1P_{1.5}$	3826±27^{a}	3825±87^{a}	3961±26^{cd}	4330±23^{a}	4568±16^{a}	5135±39^{c}	5045±08^{a}	4949±23^{b}
Straw								
N_0P_0	803±9^{e}	784±13^{e}	1198±25de	1368±36^{e}	2975±18^{c}	3163±16^{b}	3580±21^{def}	3390±19^{f}
N_1P_0	774±15^{e}	917±15^{d}	1518±41^{cd}	1485±111^{cd}	2915±12^{c}	3136±84^{b}	3508±42^{ef}	3460±32^{f}
$N_1P_{0.5}$	1409±18^{a}	1043±17^{c}	1627±38^{c}	1585±25^{c}	3336±9^{a}	3352±10^{a}	3819±28^{b-e}	3669±16^{c-e}
$N_1P_{1.0}$	1380±16^{a}	986±29^{cd}	1955±36^{b}	1927±45^{b}	3423±12^{a}	3408±30^{a}	4031±25^{b}	3883±18^{bcd}
$N_1P_{1.5}$	1310±60^{b}	998±27^{c}	1939±9^{a}	2149±33^{b}	3427±19^{a}	3431±26^{a}	4095±13^{a}	3905±24^{bc}
Root								
N_0P_0	1296±13^{d}	1141±11^{f}	1253±46^{d}	1337±35^{bcd}	1695±08^{g}	1737±43^{fg}	1745±25^{f}	1646±23^{h}
N_1P_0	1009±17^{g}	993±14^{g}	1303±10^{cd}	1467±37^{bc}	1844±27^{ef}	1889±32de	1781±51^{e}	1680±38^{g}
$N_1P_{0.5}$	1642±16^{a}	1355±13^{c}	1363±137^{bcd}	1537±29^{b}	1970±09^{d}	2141±34^{c}	1900±33^{c}	1781±19^{e}
$N_1P_{1.0}$	1531±24^{b}	1268±24de	1483±99^{bc}	1825±53^{a}	2143±71^{bc}	2248±19^{ab}	2005±31^{b}	1885±21^{d}
$N_1P_{1.5}$	1351±14^{c}	1228±18^{e}	1781±70^{a}	1935±71^{a}	2258±30^{a}	2199±27^{abc}	2037±15^{a}	1896±14^{c}

Values are means ± standard error (n=3); LSD values of grain, straw and root of wheat; 35.3, 44.3, 23.7 maize; 85, 92, 175, chickpea; 57, 62.2, 92.5 and mung bean; 42, 58, 315, respectively.

of P applied (Figure 1). While AB-DTPA extractable Cu and Zn increased slightly with P, the increases were not significant (P>0.05). In contrast, the availability of both Cd and P significantly increased with increasing P levels in the soil. As with Cu and Zn, while pH increased slightly with added P, the differences were not significant and when compared with the control treatment, decreased with N application alone (N1P0).

4. Discussion

Grain yields for all crops increased with the increasing application of the DAP fertiliser together with the recommended doses of nitrogen (Table 7). However, biomass was decreased by adding a combination of N and P, which could be due to the addition of metals by P fertiliser and some consequential phytotoxicity.

While an increase in crop yield is expected following fertiliser application, due to the beneficial effects of applied nutrients on plant growth and metabolism, the extent of any increase depends on the plant species and/or the specific variety cropped (Nuruzzaman et al. 2006). The application of P promotes root development, photosynthesis, and crop maturity, induces plant disease resistance, and enhances water use efficiency, N fixation, translocation of sugar, and therefore crop yield (Guan et al. 2013). The application of half the recommended dose of P, as practiced by farmers, seems to be an economical option for the production of cereal and legume crops on sewage-irrigated soils. The observed decrease in biomass yield due to N application alone (N1P0) could be due to a combination of elevated metal uptake, the consequential phytotoxicity of these metals, as well as an innate P deficiency in these calcareous soils (Siebers et al. 2014). The highest levels of grain Cd for wheat and chickpea were recorded with $N_1P_{1.0}$, and with $N_1P_{0.5}$ for maize and mung bean whilst the lowest levels were recorded with $N_1P_{1.5}$ (Table 7). At the highest P application rate the biomass yield was also lowered, which undoubtedly decreased metal uptake and tissue accumulation to some extent. With higher levels of P, different processes could become more dominant for transforming readily available metals into less available species. With low levels of metals, it seems that plant processes control the metal uptake while at high levels soil reactions were mainly responsible for the uptake of metals.

Table 11: Metal translocation factors (TF) for four crop species and two varieties per species

Metal	Treatment	WHEAT		MAIZE		CHICKPEA		MUNG BEAN	
		BKR-02	AS-02	S-02	M-6520	Bital-98	P-2000	NIAB-92	NIAB-06
Cd	N_0P_0	0.98	1.01	0.51	0.57	0.59	0.91	0.91	1.16
	N_1P_0	1.46	1.33	0.70	0.84	0.80	1.26	1.52	1.41
	$N_1P_{0.5}$	1.21	1.59	0.74	0.76	0.69	0.83	1.61	1.31
	$N_1P_{1.0}$	0.74	1.12	0.80	0.71	0.69	0.62	0.53	0.74
	$N_1P_{1.5}$	0.52	1.06	0.61	0.58	0.53	0.70	0.40	0.85
Zn	N_0P_0	1.42	1.76	2.15	2.04	1.76	2.47	2.88	3.01
	N_1P_0	1.53	1.68	2.24	2.12	1.79	2.69	3.04	3.26
	$N_1P_{0.5}$	1.36	1.51	1.78	1.89	1.95	2.57	2.71	3.14
	$N_1P_{1.0}$	1.22	1.15	1.75	1.80	1.83	2.22	2.69	2.73
	$N_1P_{1.5}$	1.09	1.07	1.55	1.60	1.75	2.02	2.50	2.52
Cu	N_0P_0	0.71	0.98	0.50	0.45	0.82	0.65	1.47	1.30
	N_1P_0	1.08	1.17	0.58	0.63	0.90	0.82	1.68	1.38
	$N_1P_{0.5}$	0.95	1.05	0.54	0.59	0.83	0.69	1.63	1.36
	$N_1P_{1.0}$	0.94	0.99	0.52	0.55	0.79	0.64	1.51	1.25
	$N_1P_{1.5}$	0.75	0.87	0.43	0.42	0.71	0.61	1.37	1.11

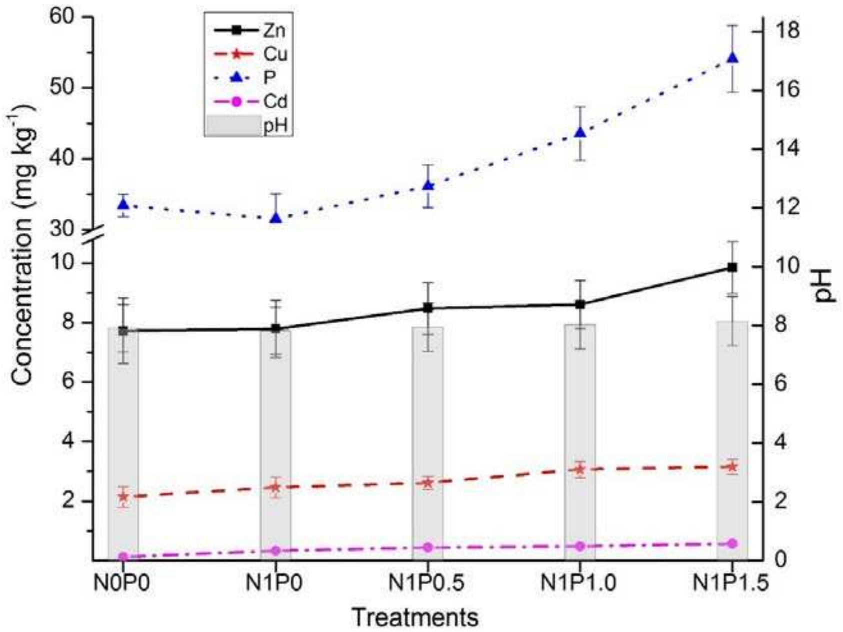

Figure 1: Effect of fertiliser treatments on post-harvest AB-DTPA extractable Cd, Zn, Cu, P and pH in soil

The increased tissue accumulation of Cd at low levels may be due to ion exchange reactions with Cd and competing ions from the fertiliser at sorption sites in the soil or by soil acidification (Grant 2011). It is well documented that phosphate reduces soil solution Cd and its mobility by forming metal precipitate with low solubility products such as Cd_2PO_3, $Cd_3(PO_4)_2$, $Cd(OH)_2$ or $CdCO_3$, which tend to be recalcitrant and generally unavailable to plants (Huang et al. 2012).

Reduced tissue Cd may also be due to P induced sorption of Cd in the soil (Siebers et al. 2014), increased surface charge, or co-adsorption of P and Cd as an ion pair (Grant 2011).

The immobilization of metal at very high rates of P, normally above those used for crop produc-tion, could be due to P-induced metal adsorption and/or precipitation/co-precipitation (Grant 2011). Decreases in Cd concentrations in plants following sorption sites in the soil application of P fertilisers have also been reported recently by several other research groups (Huang et al. 2012). In most of these studies, the reduction in Cd phyto-availability could be related to high P availability, which decreases Cd uptake by either interfering with Cd translocation from the roots to shoots or promoting the capability of the soil or its constituents to adsorb or precipitate Cd (Mar et al. 2012).

Antagonistic interactions between P and Zn are often significant in soil-plant systems, especially when only one of them (either P or Zn) is applied through a fertiliser amendment (Lambert et al. 2007). The interactions between the two elements are complex because while P interferes with Zn uptake. P also increases plant yield and thus causes sorption sites in the soil dilution of Zn tissue concentrations. P-induced increases in crop yield may also improve the ability of the crop to remove Zn from the soil, by increasing root growth or enhancing mass flow and transpiration (Lambert et al. 2007). Increased Cd desorption from the soil could increase the phyto-availability of Cd, leading to increased competition between Zn and Cd for plant uptake and translocation by the plant (Grant et al. 1998). Thus the interactions between Zn, Cd and P may have a significant effect on their overall accumulation in plant tissues (Imtiaz et al. 2006). Likewise, sorption sites in the soil application of both P and Zn may also interact to reduce Cu tissue content, which is believed to occur at the site of absorption possibly with Cu precipitation at the root surface (Fageria et al. 2001).

Nitrogen treatment alone increased the tissue concentration of all tested metals (Cd, Cu and Zn) because this treatment substantially decreased soil pH (Figure 1) and is also known to influence rhizosphere composition, microbial activity and root growth (Wangstrand et al. 2007). Ammonium-based fertilisers (urea; NH_4-N) have increased the phyto-availability of metals more than nitrate fertilisers due to a reduction in soil pH, possibly due to nitrification, plant uptake of NH_4^+ and H^+ extrusion through roots, thus causing an increase in hydrogen ion (H^+) levels in the soil (Avci and Deveci 2013). Mean Cd concentrations increased in the order of maize > chickpea > mung bean > wheat while Cu accumulation patterns were in the order mung bean > wheat > chickpea > maize, and those of Zn were wheat > chickpea > mung bean > maize. Since mung bean and maize were sown in summer, high concentrations of Cd may in part be due to high evapotranspiration (Prasad 2004). These differences in metal accumulation could be due to both morphological and genetic differences between species and varieties (Nuruzzaman et al. 2006). Many plant species increase root formation and exudation of a number of moieties, such as citrate and malate, as a mechanism for increasing P availability (Jones and Oburger 2011).

Wheat, chickpea, mung bean and maize grains respectively accumulated 4.8, 3.3, 7.7 and 3.76 times less Cd than roots and 3.8, 1.3, 7.0 and 1.5 times lower Cd than straw. The highest metal concentrations were always found in the plant roots irrespective of the species. A number of factors including anatomical, biochemical and physiological may contribute to metal accumulation and distribution in the upper vegetative parts. Since metals here were mainly restricted to the roots, this suggests that binding by negative charges of conducting tissues, pectic sites and hystidyl groups of cell walls (Hall 2002) may be important and that upward movement may be related to saturation kinetics. Some metal binding protein in roots was also considered responsible for restriction (Lux et al. 2011).

There seems to be no national policy in effect on the sustainable use of wastewater in Pakistan. Laws and regulations have been formulated about the treatment and disposal of wastewater in the country but their implementation due to a lack of resources and skilled manpower is the real issue. The result is that, while an appropriate and necessary administrative capacity exists on paper, its effectiveness is seriously curtailed in practice due to these shortcomings. An environmental impact assessment (EIA) system is mandatory but seldom followed in the public sector, and environmental laboratories have been established in all provinces but function with skeletal staff and budgets inadequate even for their routine equipment and chemical needs. Similarly, environmental tribunals have been created but their capacity to deal with reported cases is extremely restricted, as minimal personnel have been deputed in only two provinces to collectively oversee the entire country.

5. Conclusion

While DAP fertilisers are a considerable source of added metals to agricultural soils, the application of P at all levels was effective in decreasing the phyto-availability of three metals (Cd, Cu and Zn) present in calcareous soils irrigated with city waste. The most economically viable option for reducing metal toxicity in crops involved using only half of the recommended dose of P fertiliser. While this study was restricted to four plant species, these initial findings may have wide applications for the safer crop production of monocot species grown on untreated soils irrigated with city sewage.

6. Future Recommendations

Background knowledge of the factors affecting the mobility, availability, bioaccumulation and mechanisms of heavy metal uptake by cereals and legumes need to be elucidated due to difference in their physiology and root morphologies. Previous studies have also shown that heavy metals can be translocated to the grain/seeds via different tissues (Murtaza et al. 2015; Murtaza et al. 2016). However, information on their dynamics still requires further research, especially in important legume and cereals crops.

1. The high quantity of beneficial metals (Co, Cu, Fe, Mn, Mo, Ni, and Zn) in the harvested biomass (cereals and legumes) can be "diluted" to acceptable levels by combining contaminated biomass with clean matter (free of metals) in formulations of fertiliser and fodder.
2. The in situ chemical immobilisation of heavy metals is not only a cost-effective remediation strategy, which stabilises heavy metals in contaminated soil, but can also improve soil fertility, and ultimately increase plant growth. Organic amendments (compost) contain a high proportion of humified organic matter and could decrease heavy metal bioavailability in soil due to having a large surface area and thus provide strong adsorption sites, even though temporally, thus allowing vegetation to re-establish.
3. The role of NPK fertilisers and organic amendments like farm manure or inorganic additives like lime, gypsum, zeolites and Fe oxides were found to be effective in decreasing the transfer of metals into crops. Most of these materials are easily available in large amounts and their incorporation into the soil is easy if the contamination is restricted to topsoil. However, repeated application may be necessary and the effectiveness is largely dependent on soil conditions and has to be proved periodically.
4. Further effective methods to reduce metal transfer into the food chain include crop rotation and the cultivation of industrial or bio-energy crops. The selection of crops under a sewage-irrigated agriculture system needs further investigations for final recommendations to be given to growers.
5. The treatment of industrial/civic water through the coupling of physical, chemical and biological processes for the safe use of wastewater, along with strict legislation and awareness at a national

level, is the requirement of the day. Moreover, capacity building for research related to the treatment, management and safe use of wastewater is also needed. This can be achieved through arranging farmer group meetings, including print and electronic media.

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References

Akgiray O. 2005. "Explicit solutions of the Manning equation for partially filled circular pipes." *Canadian Journal of Civil Engineering* 32:490–499.

Avci H, Deveci T. 2013. "Assessment of trace element concentrations in soil and plants from cropland irrigated with wastewater." *Ecotoxicology and Environmental Safety* 98:283–291.

Ekmekci Y, Tanyolac D and Ayhana B. 2008. "Effects of cadmium on antioxidant enzyme and photosynthetic activities in leaves of two maize cultivars." *Journal of Plant Physiology* 165:600–611.

Ensink JHJ, Simmons RW and van der Hoek W. 2004. "Wastewater use in Pakistan: The cases of Haroonabad and Faisalabad." In *Wastewater Use in Irrigated Agriculture: Confronting the Livelihood and Environmental Realities*, edited by Scott, C. A., Faruqui, N. I. and Raschid, L., 91–99. Wallingford: CAB International.

Fageria NK, Baligar VC, Jones CA. 2001. "Growth and mineral nutrition of field crops." *CRC Press.*

Gopal R, Rizvi AH. 2008. "Excess lead alters growth, metabolism and translocation of certain nutrients in radish." *Chemosphere* 70:1539–1544.

Grant CA. 2011. "Influence of phosphate fertiliser on cadmium in agricultural soils and crops." *Agriculture and Agri-Food Canada* 54:143–155.

Grant C, Buckley W, Bailey L, Selles F. 1998. "Cadmium accumulation in crops." *Canadian Journal on Plant Science* 78:1–17.

Guan G, Tu S, Li H, Yang J, Zhang J, Wen S, Yang L. 2013. "Phosphorus fertilization modes affect crop yield, nutrient uptake, and soil biological properties in the rice-wheat cropping system." *Soil Science Society of America Journal* 77:166–172.

Hall J. 2002. "Cellular mechanisms for heavy metal detoxification and tolerance." *Journal of Experimental Botany* 53:1–11.

Huang H, Li T, Gupta D, He Z, Yang X-e, Ni B, Li M. 2012. "Heavy metal phytoextraction by Sedum alfredii is affected by continual clipping and phosphorus fertilization amendment." *Journal of Environmental Sciences* 24:376–386.

Imtiaz M, Alloway BJ, Memon MY, Khan P, Siddiqui SH, Aslam M, Shah SKH. 2006. "Zinc tolerance in wheat cultivars as affected by varying levels of phosphorus." *Communications in Soil Science and Plant Analysis* 37:1689–1702.

Jones DL, Oburger E. 2011. "Solubilization of phosphorus by soil microorganisms." In *Phosphorus in Action*, 169–198. Springer.

Kim KR, Owens G, Naidu R, Kwon SI. 2010. "Influence of plant roots on rhizosphere soil solution composition of long-term contaminated soils." *Geoderma* 155:86–92.

Lambert RI, Grant C, Sauva SB. 2007. "Cadmium and zinc in soil solution extracts following the application of phosphate fertilisers." *Science of The Total Environment* 378:293–305.

Lux A, Martinka M, Vaculík M, White PJ. 2011. "Root responses to cadmium in the rhizosphere: a review." *Journal of Experimental Botany* 62:21–37.

Mar SS, Okazaki M, Motobayashi T. 2012. "The influence of phosphate fertiliser application levels and cultivars on cadmium uptake by Komatsuna (Brassica rapa L. var. perviridis)." *Soil Science and Plant Nutrition* 58:492–502.

McGowen S, Basta N, Brown G. 2001. "Use of diammonium phosphate to reduce heavy metal solubility and transport in smelter-contaminated soil." *Journal of Environmental Quality* 30:493–500.

Murtaza G, Javed W, Hussain A, Wahid A, Murtaza B and Owens G. 2015. "Metal uptake via phosphate fertiliser and city sewage in cereal and legume crops in Pakistan." *Environmental Science and Pollution Research International* 22:9136–9147.

Murtaza G, Javed W, Hussain A, Qadir M and Aslam M. 2016. "Soil applied zinc and copper suppress cadmium uptake and improve the performance of cereals and legumes." *International Journal of Phytoremediation* (Accepted).

Murtaza G, Haynes RJ, Naidu R, Belyaeva ON, Kim KR, Lamb DT and Bolan NS. 2011. "Natural attenuation of Zn, Cu, Pb and Cd in three biosolids-amended soils of contrasting pH measured using rhizon pore water samplers." *Water Air Soil Pollution* 221:351–363.

Nuruzzaman M, Lambers H, Bolland MD and Veneklaas EJ. 2006. "Distribution of carboxylates and acid phosphatase and depletion of different phosphorus fractions in the rhizosphere of a cereal and three grain legumes." *Plant Soil* 281:109–120.

Prasad R. 2004. "OFDM for wireless communications systems." In *Artech House universal personal communications series.*

Purushotham D, Rashid M, Lone MA, Rao AN, Ahmed S, Nagaiah E, Dar FA. 2013. "Environmental impact assessment of air and heavy metal concentration in groundwater of maheshwaram watershed, Ranga Reddy district, Andhra Pradesh." *Geological Society of India* 81:385¬3–96.

Sarwar N, Malhi SS, Zia MH, Naeem A, Bibi S and Farid G. 2010. "Role of mineral nutrition in minimizing cadmium accumulation by plants." *Journal of the Science of Food and Agriculture* 90:925–937.

Siebers N, Godlinski F, Leinweber P. 2014. "Bone char as phosphorus fertiliser involved in cadmium immobilization in lettuce, wheat, and potato cropping." *Journal of Plant Nutrition and Soil Science* 77:75–83

Wangstrand H, Eriksson J, Ã–born I. 2007. "Cadmium concentration in winter wheat as affected by nitrogen fertilization." *European Journal of Agronomy* 26:209–214.

Zhang F, Shen J, Zhang J, Zuo Y, Li L, Chen X. 2010. "Chapter one – rhizosphere processes and management for improving nutrient use efficiency and crop productivity: implications for China." *Advances in Agronomy* 107:1–32.

SECTION III:

POLICY & IMPLEMENTATION ISSUES

CASE 11

Government Supported Farmers Utilising Wastewater in Irrigation: The Case of the South African Government in Lebowakgomo in the Limpopo Province Supporting Farmers Producing Vegetables (South Africa)

T. Gomo [1]

Abstract

In the face of dwindling fresh water resources, wastewater has been used to enhance food production through irrigation. Governments across the world have developed and implemented policies that promote the safe reuse of wastewater, but in developing countries, the lack of resources has hindered the implementation of these policies. In South Africa, the government has provided for the safe discharge of effluent into water sources (National Water Act 36 of 1998) and has also published guidelines and policies that support the reuse of wastewater in irrigation (Government Gazette 36820, Notice 665, September 6, 2013). This study, which is still in progress, is assessing the effort of the Government through its various departments in promoting the safe reuse of wastewater along the Chuenes River. The Lebowakgomo waste-treatment plant deposits treated wastewater into the Chuenes River. Three farmers along the Chuenes River who have received assistance from government departments have so far been included in

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this study. The preliminary results show the sewerage treatment plant is operating at 200% of its capacity and does not test the quality of the water released into the river. The farmers are not registered to use the wastewater as required by law and the community does not support the farmers that want to use the wastewater. There is legislation that governs the reuse of wastewater but it is not being enforced.

Keywords: wastewater in irrigation, government support, community education

1. Introduction

Water for food production is increasingly becoming scarcer owing to increased demand from other uses such as domestic, industrial and environmental users (Perry 2005, Gomo et al 2014), which give higher economic and social returns. This has in most instances forced farmers, particularly in the peri-urban locations, to utilise wastewater from large cities and towns around the world for irrigation. However, in developing countries where resources are not available for the adequate treatment of wastewater, there are greater health risks in the use of wastewater. Some governments in developing countries have developed policies and started to implement guidelines that promote the safe use of wastewater for irrigation. The problem, however, has been the enforcement of these policies and regulations mainly owing to a lack of resources.

This has been the case in South Africa, where wastewater is deposited back into rivers and streams and is then abstracted by different farmers downstream to produce food. A case in point is the Chuenespoort River in Lebowakgomo in the Limpopo Province.

This case documents the efforts that the government of South Africa has made in supporting farmers in using wastewater for irrigation and focuses on Lebowakgomo and the surrounding farmers. The study is still in progress, and as such only provides preliminary results.

2. Government Support in Wastewater Reuse in Agriculture

The South African government has taken various steps to support farmers who use wastewater for irrigation. The National Water Act 36 of 1998 addressed a number of grey areas that had been existent before independence on the rights of farmers to use water. This included smallholder farmers in small towns. The Act also sought to regulate the discharge of wastewater into clean water resources and the use of wastewater in food production in Section 37 (1) *a*.

As a result of this section of the Act, the government has been able to gazette regulations pertaining the use of wastewater for irrigation, the most recent being *Government Notice 665 in Government Gazette 36820, dated September 6, 2013*. Through such regulations and policies, the government has assisted in ensuring that the quality of treated water discharge into water resources and the reuse of wastewater in irrigation is controlled. Table 1 below shows quality of wastewater allowed to be used in irrigation per day.

The South African government has also requested the registration of any farmer using wastewater and the keeping of records on the quantity, measured weekly, and the quality on a monthly basis. Each wastewater user should be registered with a regulating authority in the area where they intend to irrigate, and should receive a certificate. Irrigation with wastewater should not be above identified major aquifers and should at least have the following boundaries (*RSA Government Notice 665 in Government Gazette 36820, September 6, 2013*):

- At least 50 m above the 1 in 100 year flood line or riparian habitat whichever is the greatest, or alternatively at least 100 m from a water course whichever is the greatest, or at least further than 500 m radius from a borehole that is utilised for drinking water or stock watering;
- On land that is not, or does not, overlie a major aquifer; and
- Outside at least a 500 m radius from the boundary of a wetland.

The government has also put in place legislation that ensures that all wastewater treatment plants are registered and the quality of water discharged into water resources is monitored on a weekly basis. The siting and location of any wastewater treatment plant is also regulated

Table 1: Quality of Wastewater to be Used for Irrigation in South Africa

VARIABLES	LIMITS PER DAY		
	50 m³	500 m³	2,000 m³
pH	not less than 6 or more than 9 pH units	not less than 6 or more than 9 pH units	not less than 5.5 or more than 9.5 pH units
Electrical Conductivity	not exceed 200 milliSiemens per meter (mS/m)	not exceed 200 milliSiemens per meter (mS/m)	does not exceed 70 milliSiemens above intake to a maximum of 150 milliSiemens per meter (mS/m)
Suspended Solids			does not exceed 25 mg/l
Chloride as Free Chlorine			does not exceed 0.25 mg/l
Fluoride			does not exceed 1 mg/l
Soap, Oil and Grease			does not exceed 2.5 mg/l
Chemical Oxygen Demand	does not exceed 5,000 mg/l after removal of algae	does not exceed 400 mg/l after removal of algae;	does not exceed 75 mg/l
Fecal coliforms	do not exceed 100,000 per 100 ml	do not exceed 100,000 per 100 ml	do not exceed 1,000 per 100 ml
Ammonia (ionised and un-ionised) as Nitrogen			does not exceed 3 mg/l
Nitrate/Nitrite as Nitrogen			does not exceed 15 mg/l
Ortho-Phosphate as phosphorous			does not exceed 10 mg/l
Sodiu Adsorption Rate (SAR)	does not exceed 5 for biodegradable industrial waste-water	does not exceed 5 for biodegradable industrial waste-water	

Source: Government Gazette 36820, September 2006

through legislation. When treated wastewater is to be discharged into a water resource, general and special limits have been set as shown in Table 2 below.

With these policies and regulations, and others that have not been described here, the Government of South Africa has been able to help farmers that are using wastewater for irrigation to some extent. However, despite all these good policies and financial support the government has provided to these farmers, enforcement has been elusive mainly due to a lack of resources and skills. A case in point are the farmers along the Chuenes River in Lebowakgomo.

3. Study Site

Lebowakgomo is a small town located ±50 km to the south-east of Polokwane, the provincial capital of the Limpopo Province of South Africa. The town is in Lepelle-Nkumpi local municipality and has a human population of around 35,000 (SA population statistics, 2012). The geographical location of the town is 24°15'30.76"S, 29°38'59.7"E.

Figure 1: Location of Lebowakgomo in South Africa

Table 2: General and Limits for the Discharge of Treated Wastewater into a Water Resource in South Africa

SUBSTANCE/PARAMETER	GENERAL LIMIT	SPECIAL LIMIT
Faecal Coliforms (per 100 ml)	1,000	0
Chemical Oxygen Demand (mg/l)	75 (i)	30(i)
pH	5.5-9.5	5.5-7.5
Ammonia (ionised and un-ionised) as Nitrogen (mg/l)	6	2
Nitrate/Nitrite as Nitrogen (mg/l)	15	1.5
Chlorine as Free Chlorine (mg/l)	0.25	0
Suspended Solids (mg/l)	25	10
Electrical Conductivity (mS/m)	70 mS/m above in-take to a maximum of 150 mS/m	50 mS/m above back-ground receiving water, to a maximum of 100 mS/m
Ortho-Phosphate as phosphorous (mg/l)	10	1 (median) and 2.5 (max-imum)
Fluoride (mg/l)	1	1
Soap, oil or grease (mg/l)	2.5	0
Dissolved Arsenic (mg/l)	0.02	0.01
Dissolved Cadmium (mg/l)	0.005	0.001
Dissolved Chromium (VI) (mg/l)	0.05	0.02
Dissolved Copper (mg/l)	0.01	0.002
Dissolved Cyanide (mg/l)	0.02	0.01
Dissolved Iron (mg/l)	0.3	0.3
Dissolved Lead (mg/l)	0.01	0.006
Dissolved Manganese (mg/l)	0.1	0.1
Mercury and its compounds (mg/l)	0.005	0.001
Dissolved Selenium (mg/l)	0.02	0.02
Dissolved Zinc (mg/l)	0.1	0.04
Boron (mg/l)	1	0.5

Source: Government Gazette 36820, September 2006

The Chuenes River is a small perennial river that runs from the mountains around Chuenespoort dam, passes through Lebowakgomo and feeds into the Oliphants River. When the river passes through Lebowakgomo, some treated wastewater from the small town`s treatment plant is deposited. Farmers extract water along the way on a section of the river before and after the discharge of wastewater into the river. The wastewater treated at the plant is mainly from domestic uses and could probably be a factor in maintaining its perennial status.

3.1 The Lebowakgomo Waste Treatment Plant

The plant is located on the outskirts of the Lebowakgomo town. The design capacity of the plant is 90 mega litres (ML) per month but is currently operating at between 180-270 ML per month. The scheme caters for sections A, P, Q and S of the residential areas. Other sections F and B are catered for by the oxidation dams and a wetland on another treatment plant which discharges into an artificial wetland.

The plant receives waste through an underground pipeline system, and upon arrival the waste is screened to remove solids. The solids are manually removed and buried within the plant premises. The volume of wastewater is then measured through a V-notch weir, shown in Figure 2, as it proceeds to the activated sludge tank.

a) Wastewater is received here and physical debris is manually removed

b) The V-notch used to measure the received waste-water

Figure 2: Physical screening of solid waste and V-notch weir at Lebowakgomo wastewater treatment plant

After the activated sludge process, the wastewater flows to the clarifier where solids are allowed to settle and the liquid flows to the chlorination tank. Chlorine is added to the water before it is released into the Chuenes River. The quality of the water is currently not checked after treatment.

After the water has been released into the river, several farmers use the water to irrigate downstream. Three farmers who have received support from the government have been selected for this study and interviewed. These farmers mainly produce vegetables for the local communities and the Lebowakgomo town with the aim, however, of producing for the larger city of Polokwane 50 km away.

3.2 Supported Farmers

The three farmers selected are the Chuene plot, Sekonya Agricultural Research Project plot, and Mohla Agricultural Primary Co-operative owning and producing vegetables on 2, 4 and 3 hectares, respectively. The support that the government has provided to these farmers includes the provision of irrigation infrastructure such as fencing, tanks and pipes, and agricultural extension services. The extent of other support is yet to be verified in this on-going study.

3.2.1 Chuene Plot

The Chuene plot is a 2 ha plot along the Chuenes River producing vegetables such as tomatoes, onions, and spinach. The produce is sold to the local market in Lebowakgomo town about 8 km away and the surrounding Mamaolo community.

The farmer has received support from the government for fencing his plot, getting seeds, and receiving extension services from the government through the Department of Agriculture. The farmer is aware that the water from the river is wastewater but still opts to use it due to the easy availability of that water. The farmer is not willing to register as a water user to avoid paying for that water, however he is aware that he needs to register but not sure which offices to approach.

The farmer has been facing challenges with the Mamaolo community not willing to buy his produce as they have perceptions about the produce. Some are aware that the water is from the wastewater treatment plant while others shun the vegetables because people have committed suicide along that river stretch. Some villagers have even approached the farmer to warn him against that water.

As a result, the farmer has reduced production because he is afraid of the community and in some instances his equipment has been vandalised. The farmer has also drilled a borehole to supplement the water and during instances when he is not using the water from the river due to community issues. Figure 3 below shows the Chuenes plot with a small vegetable shop on site and part of the Chuenes River where the farmer abstracts water using a portable system laid over the ground.

Figure 3: Chuene Plot

3.2.2 Sekonya Agricultural Research Project plot

Sekonya Agricultural Research project plot is a 3 ha plot that produces vegetables under drip. The farmer uses the water from the Chuenes River and pumps it into a 60,000 L steel storage tank provided by the government through the Department of Rural Development.

The farmer then irrigates using a drip irrigation system producing crops including tomatoes, spinach and cabbages intended for the Lebowakgomo market.

The farmer is aware that the water he is using is wastewater but because it is readily available and cheap, he uses it for production. The farmer is not a registered water user despite legislation requiring that he becomes registered. Figure 4 below shows part of the farm and the infrastructure that was provided by the government.

Figure 4: Sekonya Agricultural Research Project plot

The farmer has also encountered problems with the community not supporting his project owing to the use of wastewater. This has caused a reduction in production at the farm.

3.2.3 Mohla Agricultural Primary Co-operative Plot

The Mohla plot is located about 12 km from Lebowakgomo town along the Chuenes River. The co-operative is run by three members of the Malemang community. The cooperative has received support from the government in the form of irrigation equipment, training and agricultural extension services as well as production inputs. The main vegetables that they produce are spinach, butternuts, green pepper and carrots for the Lebowakgomo market.

The farmers use sprinkler and furrow irrigation methods with water from the Chuenes River. The farmers are aware that it is wastewater but are not registered as water users. The Malemang community has also been causing problems over the usage of the wastewater, in some instances opting to buy vegetables from the larger supermarkets in Lebowakgomo town. The effects of the community's actions have seen a reduction in production at the plot. Figure 5 below shows some of the vegetables at Mohla plot.

Figure 5: Mohla Agricultural Primary Co-operative plot

4. Conclusion

It should be noted that this is an ongoing study and the conclusions are only preliminary. A full study report will have firm conclusions. It is concluded in this study that the government of South Africa acknowledges the importance of wastewater and has put in place policies to support the safe use of wastewater in food production. The government is also assisting farmers who want to utilise wastewater for food production but due to a lack of resources the policies have not been enforced.

Farmers are using the wastewater because it is readily available and cheap, but are not registered as requested by law probably because they do not want to pay for the water. The farmers are aware that they should register as water users. The wastewater treatment plant does not have the capacity to test the quality of the water that it discharges into the Chuenes River.

All the farmers along the Chuenes River are facing similar problems with communities that are not supportive of the use wastewater in food production. More may need to be done to educate the community on use of wastewater in food production.

References

Gomo T., Senzanje A., Mudhara M. and Dhavu K. 2014. "Assessing the performance of smallholder irrigation and deriving best management practices in South Africa." *Irrigation and Drainage Systems* 63:419–429.

Perry C. 2005. "Irrigation reliability and the productivity of water: A proposed methodology using evapotranspiration mapping." *Irrigation and Drainage Systems* 19:211–221.

South African Government. 1998. "The National Water Act 36 of 1998."

South African Government. 2013. "Government Notice 665 in Government Gazette 36820, 6 September 2013."

South Africa Statistics. 2012. "Population of South Africa."

CASE 12

Challenges in Implementing Standards for Reuse of Treated Wastewater in Irrigation: The Case of Bolivia (Bolivia)

Juan Carlos Rocha Cuadros [1]

Abstract

This study is based on the work sponsored by PROAGUAS - COTRIMEX to establish regulations for the reuse of treated wastewater and looks at the stages of studying laws and regulations in force, the control parameters proposal, the relationship with World Health Organization (WHO) guidelines and the sustainability of applying the regulations via the implementation of subsidies to the irrigation system as a whole.

Reference is made to the difficulties encountered at all the stages mentioned and the proposals that have been made to overcome them and reach the stage of formulating the regulations.

Keywords: reuse of treated wastewater, Bolivia, implementation of standards, irrigation, sustainability

1. Introduction

For many years now, there have been efforts in Bolivia to create an irrigated agricultural area that could somehow be sufficient to provide food for the country's population. In this context, various cooperation

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agencies have invested resources to establish a professional basis for managing the technical aspect of irrigation, especially in medium-sized and large irrigation projects, and simultaneously to set up offices to support the implementation of irrigation projects from a corporate point of view.

As part of this task, construction work has been carried out on Bolivia's irrigation infrastructure and to give a complete picture of the situation regarding irrigation there are several publications including "Systematisation of treatment and reuse of wastewater".

During the course of the construction work, it was noted that another type of irrigation was being used, which did not have purpose-built head works, particularly in the Andean region of Bolivia, where water is a naturally scarce resource. This adds the task of identifying populations who were using sewage, either treated or untreated, for irrigation, having arrived at the conclusion that the majority of the populations experiencing water scarcity use untreated sewage in municipalities with a wastewater treatment plant (WWTP) that does not function properly due to lack of maintenance, and therefore the situation is identical to that of those who use untreated sewage for irrigation.

This general picture has prompted authorities in charge of irrigation in Bolivia to try and develop regulations which take into account not only the technical options for treating water but also the sustainability of measures to be taken, given the lack of operation and maintenance seen in various municipalities.

2. Irrigation with Treated or Untreated Sewage in Bolivia

Triangular cooperation between Mexico, Germany and Bolivia (COTRIMEX), has encouraged the investigation and reporting of proposals for the use of treated water in irrigation. During the period from 2012 to 2014, 111 irrigations systems using treated or untreated sewage were built in the Andean region and the most significant findings can be summarised as follows:

- Eighty-four WWTPs have been built in municipalities
- Thirty-one of the 84 WWTPs do not work due to problems operating and maintaining them
- Of the remaining 53 WWTPs, the efficiency of the treatment is less than 50 per cent, which means that they are not suitable for irrigation
- All the effluents are used for irrigating vegetables

The use of treated or untreated sewage for irrigation prompted the formation of a joint committee, consisting of ministries and departments of the state concerned with the matter, as well as international cooperation. Together they managed to create a plan with four strategic lines of action:

- Training strategies
- Regulatory framework strategies
- Funding strategies
- Communication strategies

3. Regulatory Framework Strategies

The development of regulations relating to this has already followed steps such as the proposal stage, which defines the need to have specific regulations; a consultant will be responsible for the preparation stage, and the discussion stage will be the responsibility of a committee including vice-ministries involved in dealing with the reuse of treated wastewater, the various departments of the state who are dependent on the vice-ministries, and international cooperation in the form of offering support and sharing experience.

The stages mentioned above are followed by surveys, then the approval and publication of the proposal. These have not yet been carried out.

The action taken to develop the proposal has taken into account the following specific points:

- A study of associated current regulations
- Proposal for the selection of parameters
- Links with WHO guidance
- Sustainability/generation of incentives

3.1. Study of current regulations

One of the greatest difficulties in creating new regulations is aligning the current regulations with the overall objective. Bolivia has Law 1333 (*Ley de Medio Ambiente 1333,* 1992), the Environment Act, which, due to its legal nature, comes above any planned regulations.

Often, aligning laws with regulations means making compromises that do not go against what is stipulated by the Law but rather respond to interpretations in such a way that allows an agreement to be reached between the parties. In particular, the Environment Act contains Water Contamination Regulations.

These regulations govern the discharge of wastewater into bodies of water and classify bodies of water into four classes, each of which has 80 physiochemical and bacteriological parameters, of which 25 are binding.

Since the enactment of Law 1333, very little has been done to classify the bodies of water and the parameters are very strict with regard to quality, to the point that applying them is almost impossible. In fact, if you take into account the technology and the quality of the water treated in the plants in major cities, total compliance with the regulations in force is not possible. Nevertheless, there also exists a set of provisional parameters (which includes classification of rivers) that are not as strict and that are used by treatment plant operators or designers in order to comply with Law 1333.

We can see then that there exists in the Environment Act a way of interpreting compliance with it through the provisional article, particularly when in the whole Law irrigation is only mentioned in the classification of bodies of water, and falls under Category A, that is to say the most stringent one: in this category the BOD_5 must be less than 2 mg/l, faecal coliforms between 5 and 50 NMP/100 ml for 80 per cent of samples, and suspended solids must be less than 10 mg/l, among other parameters.

With the Environment Act developed in this way, some sectors such as mining, industry and hydrocarbons have developed regulations (RASIM, 2002) applicable to these sectors in particular, to allow real compliance that can be monitored through mechanisms proposed in these regulations. In a sense, the various sectors have demonstrated that the application of the Environment Act must be suitable for these particular sectors and have shown a route that can also be taken by other sectors.

In the context of current institutionalisation, there have been discussions about who is in charge of what. Civil servants who work at the Vice Ministry of the Environment are zealous in the quasi strict observance of the Law and reluctant to embrace changes to the parameters in their consolidation. They have made clear requests for studies that support any proposed changes. It goes without saying that there were no stringent studies for current parameters or anything else meaning that the majority of bodies of water are not classified so far.

It has been proposed that treatment plants are seen as head works for the irrigation systems that use this water. This can define who is in charge of environmental monitoring of this type of water (Salazar, 2010). In this case the irrigation sector would be the delegated head, given that the Law places the responsibility for all environmental matters with the Vice Ministry of Environment and Water.

The proposal means a political decision must be made by the irrigation sector if it wants to see a change in the situation regarding irrigation using household sewage, given that the industrial, hydrocarbon and mining sectors have their own regulations. It is also possible that, depending on the quality of the incoming water and the type of treatment, the wastewater coming from the last two of these sectors may not be suitable for irrigation; conversely those from households have a similar physiochemical and bacteriological composition and can therefore be governed by regulations for treated household wastewater (municipal).

3.2. Proposal for the Selection of Parameters

The experiences of different countries who have regulations for irrigation have been taken into account. Nevertheless, parameters have not been applied consistently. Instead there is a range of suitable parameters for the situation in each country but with a certain emphasis on the application of the regulations created by the United States Environmental Protection Agency (EPA).

In principle, efforts have been made to choose some parameters that are as close as possible to representative values for the existing water quality. In this way the established parameters could be analysed with existing portable equipment and data can be made ready available.

Some tasks can now be carried out with portable equipment as a response to the fact that many communities have treatment plants but do not have a laboratory to measure the efficiency of the treatment in order to be able to improve the process in any given case. But it is also possible that medium-sized cities already have laboratories that can serve as a reference point for the analyses carried out in smaller towns.

The initial discussion about how many parameters should be taken into account has taken a long time due to the desire to keep parameters that, according to some participants, could not be omitted as they are included in the Environment Act. Other participants wanted to carry out further analysis of, for example, bio-indicators and others wanted detailed results based on a scientific study, giving the most suitable value limit for each parameter.

This has come to form the basis of the study of the parameters in some already established regulations that serve as a guideline (Cisneros, 2013) and that do not generate any discussion beyond that of adapting them to the national situation. Thus, it was decided to base the regulations on the experience of the EPA and the regulations in force in Mexico.

3.3. Relationship with the PAHO/WHO

One of the goals which it was attempted to include in the regulations proposal is the WHO guidelines (WHO, 2006) regarding the use of treated water in irrigation. It has been seen, however, that only large and medium-sized cities could have access to health data allowing the full implementation of the proposed guidelines.

This is a difficulty that, for now, has not been possible to overcome. Nevertheless, it is possible that many communities and small towns are not able to build large treatment plants, and here the multi-barrier guidelines proposed by the WHO can help. This involves training the people who manage the WWTPs and those who use the treated water. In view of this, a set of incentives have been proposed to ensure the sustainability of using treated water for irrigation.

4. Sustainability and Generation of Incentives

One of the requirements of the authorities that has been emphasised has been in relation to the sustainability of the measures contained in the regulations, as it is clear that farmers see water as an acquired right, and regulations for distributing irrigation water are based on this.

As a general rule, irrigation water is not paid for, as investment in head works, such as damns, far exceeds the farmers' ability to repay. It is rather a common practice for head works to be non-repayable and for the irrigation organisation to be responsible for irrigation schedules as well as the charging or working methods to carry out the maintenance of canals.

What happens with sewage is worse. The 'waste' is used for irrigation as a whole, whether in addition to clear water or as the only source of water for irrigation, and the irrigation organisation functions from the outlet from treatment plants.

As a consequence, for an area trying to use wastewater that is adequately treated for irrigation, there lies a challenge in terms of financial sustainability and communication.

One of the ideas promoted from the technical side that handles irrigation in Bolivia has been to look for mechanisms to cover the financial aspects of using treated water for irrigation. Thus, a subproject has been created to check the places that are irrigated with treated water and the overall situation, including the functioning of the plants, the costs involved and the use of irrigation in them.

The following irrigation systems were chosen for the study: Patacamaya and El Alto (La Paz); Cochabamba, Punata and Cliza (Cochabamba); Sucre and Yotala (Chuquisaca); Tarija, Uriondo and San Lorenzo (Tarija); Betanzos and Puna (Potosí); Comarapa (Santa Cruz); and Caracollo and Eucaliptus (Oruro).

For all treatment plants a methodology has been developed and involves, firstly, the location of the WWTP and its area of influence. The treatment method and its efficacy have been assessed and the costs for operating and maintaining the plants, and how to meet them, have been determined. The following table shows a summary of the findings.

Name of WWTP	Location and area of influence	Methodology and efficiency of treatment	Treatment costs	WWTP sustainability
Patacamaya	Has two treatment plants. The municipality of Patacamaya is situated 101 km from the city of La Paz. The effluents from treatment plants discharged into the river are used in agriculture, principally for fodder plants.	The two WWTPs use similar treatment methods: preliminary treatment (screens and grit chambers), primary treatment (Imhoff tanks), secondary treatment (biological filters), and tertiary treatment (maturation ponds). For similar flows of approximately 1.0 l/s BOD5 intake 1,000 mg/l and intake of faecal coliforms of 3E7 NMP/100 ml the efficiencies are approximately 82% and 98% for the two parameters.	There are no data regarding the WWTP operation and maintenance costs; we only know that electricity consumption is paid for.	The municipality is in charge of the WWTPs and has four people working on this. It also pays for the electricity. EMAPA, which is the company that provides the service, charges each user 4 Bs to handle the sewage but although part of the tariff should be used for the operation and management of the WWTPs this does not happen in practice.
El Alto - Puchukhollo	WWTP built in 1998 serves the city of El Alto in Murillo province in the department of La Paz. The plant is currently being extended and this includes principally the addition of trickling filters and disinfection units.	The plant is being extended and currently has two sets of ponds, each one with six ponds and three trickling filters. The treated water is discharged into the Seco River. All of the water is used in irrigation; what is more, the farmers have drilled the outlet and use this water for irrigation. The BOD5 intake is 456 mg/l, efficiency of 76.75% at output. That of coliforms is 7.3E7 at intake, efficiency of 99.8%. Given that El Alto is an industrial city, there are other pollutants to be taken into account.	There is no separate payment for the operation and maintenance of the Puchukhollo WWTP: a payment is made for the drinking water service and a percentage of this goes toward the sewage service. A study[2] establishes that payment is made at a rate of m^3 of water consumed per month. The average amount paid is 0.10 US$/$m^3$.	EPSAS has an annual expenses plan. This includes energy, staffing review, maintenance, waste, and administration. Taking into account the WWTP's production, which is approximately 430 l/s, the cost involved is 0.22 Bs/m^3 (0.0315 US$/$m^3$)

[2] *Identification Study 'Mejoramiento del Abastecimiento de Agua Potable Ciudad El Alto' (Improving Supply of Drinking Water in the City of El Alto) Consultora RIMAC, 2013*

Name of WWTP	Location and area of influence	Methodology and efficiency of treatment	Treatment costs	WWTP sustainability
Alba Rancho – Cochabamba	Wastewater from the city of Cochabamba is drained into the treatment plant situated in the Alba Rancho area, to the south of the city. The Alba Rancho WWTP started operating in 1986.	The treatment plant has four primary ponds over an area of 13.7 ha, and eight secondary ponds over an area of 21.9 ha. It also has a network of distribution channels and collection channels, and their flow meter systems. The efficiency of BOD5 removal is 68% for an intake concentration of 275 mg/l and for faecal coliforms is 96.33% for an intake of 5.8E7 NMP/100 ml.	There is no separate payment for the operation and maintenance of the Alba Rancho WWTP, part of the payment for sewage covers this area and SEMAPA, which is the operator, has reported for the second management quarter an average cost for sewage services of 4.92 Bs/m^3. (0.7 US$/$m^3$).	SEMAPA has an annual expenses plan This includes energy, staffing review, maintenance and administration. Taking into account the WWTP's production, which is approximately 463 l/s, the cost involved is 0.18 Bs/m3 (0.026 US$/$m^3$).
Punata Colque Rancho	WWTP completed in 2000 with a system of stabilisation ponds. Subsequently in 2007 the University installed wetlands. The farmers have organised an irrigation system with the construction of canals. They use this water for fallow.	Originally, this WWTP had two anaerobic ponds operating in parallel, each one followed by a facultative pond and finally three maturation ponds operating in parallel. At the end of this treatment process there are wetlands for research purposes. The assessment carried out by UMSS in 2012 reports efficiency of about 83% for BOD5 (initial concentration of 432 mg/l) and about 90% for faecal coliforms (1.4 E6 UFC/100ml intake concentration)	There are no data regarding the operation and maintenance costs of the WWTPs.	The municipality allocates 45,000 Bs for sewage, including three treatment plants, one of which is Colque Rancho. In this area, the irrigators take part in maintaining the WWTP, cleaning the WWTP grounds once a year. Six communities make use of this water, making a total of 300 people who use the water for two hours.

Name of WWTP	Location and area of influence	Methodology and efficiency of treatment	Treatment costs	WWTP sustainability
El Campanario - Sucre	The WWTP is located in Campanario, belonging to the second district of the Municipality of Yotala in the north-eastern part of the department of Chuquisaca, 11 km from the city of Sucre.	This plant has facilities for pre-treatment, consisting of screens, grit chambers and flow meters; primary treatment with Imhoff tanks; secondary treatment with trickling filters and secondary sedimentation ponds and maturation ponds as well as facilities for sludge treatment. The efficiency of BOD5 removal is 76% for an intake concentration of 340 mg/l	There is no separate payment for the operation and maintenance of the El Campanario WWTP; part of the payment for sewage covers this. The average tariff for the drinking water and sewage service is around 4 Bs/m^3	ELAPAS has an annual expenses plan. This includes energy, staffing review, maintenance and administration. Taking into account the WWTP's production, which is approximately 132 l/s, the cost involved is 0.62 Bs/m3 (0.089 US$/m3)

Source: COTRIMEX, "Study of Tariffs and Subsidies for WWTPs in Bolivia (Estudio de Tarifas y Subsidios para las PTAR en Bolivia)". Document under review, 2015.

The summary in the previous table shows how little importance is given to the treatment of the wastewater. In fact, it is only in the capital cities that the Providing Entity of Water and Sewage Services (EPSA) keeps accounts of what it spends on a WWTP. Therefore, sustainability in medium-sized and small cities is tied to what the municipality wants to invest but only as part of the total maintenance of sewage systems. In fact, in the majority of cases, no financial or human resources are allocated exclusively to a WWTP.

Ideas have been put forward regarding how to organise grants at the design, construction and operation stages of irrigation systems using treated water.

For the design stage, the grant should be 100 per cent and the technical aspect should include a strong social dimension for communicating treatment targets, and the use of multi-barriers to monitor the risks from the production chain to the consumption of products that have been irrigated with treated wastewater.

At the construction stage, a grant of up to 80% has been recommended. For the rest of the funding, 15% would come from the municipality and 5% would come from the irrigators to allow the complete irrigation system to be equipped, that is to say the WWTP and the irrigation water distribution channels. Of course, technical sustainability needs to be ensured, that is to say it should be clear how the efficiency of the WWTP is going to be monitored and how its operation and maintenance are going to be organised. Irrigation associations should also already be trained in managing the treated water.

It has been proposed that incentives should go to municipalities or entities that manage the treatment plants to cover its operation and maintenance costs, provided that targets relating to the quality, operation and maintenance of WWTPs are met. Incentives have also been proposed for irrigators in marketing their products (green products), provided that they comply with the multi-barrier guidelines for managing the use of treated sewage for agricultural irrigation.

The drawback in this case is the availability of funding for the grants that have been proposed. This proposal also requires political decisions from the authorities for the use of resources that are returned to the national treasury each year due to the failure of municipalities to meet the total budgeted costs. This reinvestment in schemes for irrigation with treated water would take place in the same municipality with the advantage that health and environmental conditions can be improved through incentives and not through regulatory taxation such as that which was carried out by the comptroller's office which required municipalities to pay tax when WWTPs were set up in some capital cities.

5. Conclusions

- The Joint Commission, consisting of the three Vice Ministries of Sanitation, Environment and Irrigation, as well as International Cooperation, has been very useful for discussing the technical aspects of the measures proposed in regulations so that decisions can be made more quickly.
- The intermediate authorities need to have a proactive attitude towards change as it is these authorities who submit their reports to decision makers.
- It is necessary that the interested party, in this case the irrigation sector, not only promotes, but is also be the driving force behind all the initiatives, meetings and decisions, and ensures that they all happen. This requires its activities to be in line with a project framework that can involve international cooperation as in the case of Bolivia which has COTRIMEX where targets are shown that the authorities themselves undertake to meet in some way.
- Finally, there needs to be political commitment, both to integrate new regulations into the existing Law and to ensure the provision of funding for the proposed grants.

References

Cisneros M.C., 2013. "*Guía de referencia para el reúso de las aguas residuales en riego agrícola* (Reference guide for resuse of wastewater in agricultural irrigation)."

Consultora RIMAC, 2013. "Identification Study '*Mejoramiento del Abastecimiento de Agua Potable Ciudad El Alto*' (Improving Supply of Drinking Water in El Alto City)."

COTRIMEX, 2015. "*Estudio de Tarifas y Subsidios para las PTAR en Bolivia* (Study of Tariffs and Subsidies for WWTPs in Bolivia)." Document under review.
Ley de Medio Ambiente (Environment Act) Law No. 1333. April 1992.

Ministerio de Medio Ambiente y Agua (Ministry of Environment and Water). 2013. "*Sistematización Sobre Tratamiento y Reuso de Aguas Residuales* (Systematization of Treatment and Reuse of Wastewater)", Ministerio de Medio Ambiente y Agua (Ministry of Environment and Water).

RASIM, 2002. "*Reglamento Ambiental del Sector Industrial y Manufacturero* (Environmental Regulations for the Industrial and Manufacturing Sectors)." Supreme Decree 26736, July 2002.

Salazar L. et al. 2010. "*Sustentabilidad y Autogestión de Sistemas de Riego* (Sustainability and Self-Management of Irrigation Systems)."

Supreme Decree 24176. 1995. "*Reglamento Ambiental para Actividades Mineras* (Environmental Regulations for Mining Activities)." December 1995.

Supreme Decree 26171. 2001. "*Reglamento Ambiental del sector Hidrocarburos* (Environmental Regulations for the Hydrocarbons sector)." May 2001.

WHO. 2006. "Guidelines for the safe use of wastewater, excreta and greywater", Vol 2.

CASE 13

Community-Based Wastewater Management System in Peri-Urban Areas of Kathmandu Valley, Nepal (Nepal)

Uttam Raj Timilsina [1]

Abstract

This case attempts to present the trend of wastewater production, management and use at a community level in the Kathmandu valley (Kathmandu Lalitpur and Bhaktapur), Nepal. It also presents the current state of policy, technology and management practices and the institutional arrangements in addressing the development and management of infrastructure and services on wastewater management and the environmental, health and livelihood consequences emerging from wastewater production and use in peri-urban areas of the Kathmandu valley. Specific attention has been paid to the agricultural use of wastewater, the impacts on the agricultural production environment and the people using wastewater in the production of seasonal vegetables and crops. In presenting the use of wastewater in agriculture, attention has been paid to the existing practices of wastewater use in agriculture by the people of the Khokana community as a successful case study. The case ends with an analysis on the state of knowledge gap in the country relating to the safe use of wastewater and an assessment of the capacity building needs of the relevant

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institutions concerned with the management and use of wastewater. The analyses in the case show that the management of wastewater in the country is driven by the notion of wastewater as an 'environmental nuisance' rather than a 'resource' with the potential for safe application in agriculture and non-agricultural uses. This notion is shown to be driven by to prevalence of sectoral and disciplinary approaches in water sector development. The water sector policy environment in the country, legislation and regulatory provisions, in general, are found to favour the promotion of safe wastewater use while gaps are identified in institutional arrangements and at the implementation level. The gap in the implementation level is noted in terms of separation in the use of wastewater from the design, development and management of wastewater system and services. The opportunity, however, lies in considering wastewater as a resource and promoting the safe use of wastewater as means of ensuring and adding to agricultural water security at the local level. The knowledge system in the country and research and development on the wastewater system, practices and safe use are found to be largely deficient.

Keywords: wastewater, water quality, peri-urban, policy implementation, community-based

1. Country Context

Nepal is a landlocked mountainous country in South Asia, located between latitudes 26°22'N and 30°27'N and longitudes 80°04'E and 88°12'E, and bordered by China to the north and India to the south, east and west. With a total land area of 14.718 million ha the country is characterised by a diverse topography, geology and climate, creating opportunity and constraints for diverse land uses and livelihood patterns. Nepal is predominantly mountainous with 77% of the land area being hills and mountains and only 23% of the area, called Terai, is flat, being located along the southern border. The elevation ranges from 64 m above sea level to 8,848 m at the summit of Mount Everest, within a span of 200 km.

The total population of the country according to the population census of 2011 is 26.62 million. Nepal's economy is largely based on agriculture, which contributes to nearly 40% of GDP and provides employment for two-thirds of the population. The cultivated area of the country is 3 million ha, of which 1.766 million has is potentially irrigable. At present nearly 1.33 million ha or 44% of the cultivated area has an irrigation facility of some kind but only 17% of the cultivated area has access to year-round irrigation. Administratively the country is divided into five development regions and 75 districts. The districts are considered the key units for development planning and the delivery of administration and support services. Poverty is widely prevalent in the country with 25.4% of the population below the poverty line of 1 US$ per capita per day (NPC, 2010).

2. State and Sources of Wastewater Production

The production of wastewater in the Kathmandu valley is through domestic, commercial and industrial routes. The sewer systems in the Kathmandu valley are essentially combined sewerage and storm water drains, and also the illegal connection of sewerage to storm water drains is common in many parts of the Kathmandu valley. The direct disposal of solid and liquid wastes along the river course and rainwater runoff originating from the urban areas and agricultural lands have also been responsible for significant degradation in the water quality of the rivers and other surface water bodies. Wastewater produced from the domestic routes includes grey water and black water produced from washing, cleaning, bathing and sanitary uses. Only small numbers of houses are connected to sanitary wastewater systems and therefore most houses end up disposing the wastewater directly into the rivers and other water bodies. With a 232 km sewer system developed in the Kathmandu valley, only 40% of the population has access to a sewer facility (ICIMOD et al. 2007). Wastewater generated by industries has been another source of wastewater. A total of 4,500 industrial units of different sizes are estimated to be operating in different parts of the country. The concentration of industries is large in the Kathmandu valley. Nearly 40% of the industries in the country are estimated to be producing significant amounts of wastewater. The combined wastewater production in the three industrial estates in Kathmandu valley Balaju, Patan and Bhaktapur is estimated to be 800 m^3/day. The wastewater generated in most industries is mixed with the municipal sewerage system while solid industrial waste is collected and dumped into pits or open spaces.

No reliable data are available on the total volume of wastewater production from different sources and in the urban and rural areas of the country. In the absence of necessary information, the daily volume of wastewater production is estimated based on the average daily consumption of water per capita, which is taken as 75 litres per capita per day in urban areas and 40 litres per capita per day in rural areas, with 85% of this ending up as domestic wastewater (UNEP 2001). The volume of wastewater generated and collected in the wastewater management system in the five municipalities of the Kathmandu valley, which are the most urbanised areas in the country, is provided in Table 1.

Table 1: Wastewater Production in Municipal Areas of the Kathmandu Valley

DESCRIPTION	MUNICIPALITIES				
	Kath-mandu	Patan	Bhaktapur	Kirtipur	Madhyapur-Thimi
Volume of Domestic Wastewater Generated (MLD)	64,497	15,647	5,971	3,920	3,069
Volume of Industrial Wastewater Generated) MLD)	4,515	1,095	418	274	215
Total Waste-water Gener-ated (MLD)	69,012	16.742	6,389	4,195	3,284
Wastewater Collected (MLD)	34,506	8,371	3,195	2,097	1,642

Source: ICIMOD, MOEST/GON and UNEP 2007

3. State of Treatment and Management Services for Wastewater

The existing state of some wastewater treatment plants in operation in the Kathmandu valley and in other urban areas of the country is provided in Table 2. In 1999 the Bagmati Civilisation Integrated Development Committee (BCIDC), previously known as the High Power Committee for the implementation and monitoring of the Bagmati Area Sewerage Construction/Rehabilitation Project, was constituted with the aim of restoring environmental conditions in the Bagmati river, and constructed the Guheshwori Wastewater Treatment plant with the design capacity of 17.3 MLD of wastewater. The plant constructed with the aim of improving the Bagmati River Environment at Pashupatinath Temple has been functioning only intermittently due to high operating costs and the problem of foaming in the aeration tank.

Table 2 clearly shows that almost all of the large-scale and centralised wastewater treatment plants developed in Kathmandu are either non-functional or operating much below their design capacity. The reasons, among others, have been the higher costs of operation and maintenance and upkeep of the system. As an alternative to centralised wastewater treatment, options for decentralising the management of wastewater are being promoted by the development organisations involved with public health and environmental issues, such as UN-Habitat, Environment and Public Health Organization (ENPHO), municipalities and community groups.

Despite efforts over the past three decades, the agencies involved in public health and environmental management, including municipal bodies in the Kathmandu valley, have failed to manage the growing volume of wastewater. The problems are aggravated every year in urban areas due to the increasing volume of wastewater generation as a result of accelerated growth in the urban population, the shortage of drinking water supplies, and the inability of the government and municipalities to improve urban infrastructure and services, especially the expansion of the sanitary sewerage system and roadside and storm water drainage in urban areas. Ultimately, the sewage is dumped in the rivers without any kind of treatment.

Table 2: Existing wastewater treatment plants in the Kathmandu valley and other urban areas of Nepal

Location	Type/Stage	Capacity MLD	Present State	Service Details
Dhobighat, Patan (Kathmandu Valley)	1st Pond – Aerobic 2nd Pond – Anaerobic 3rd Pond – Facultative 4th Pond- Aerobic	15.4	Not working	HH Connections-53,900 Sewerage Lines-61,650 Combine channel- 44Km
Kodku, (Kathmandu Valley)	1st Pond – Aerobic 2nd Pond – Anaerobic 3rd Pond – Facultative 4th Pond- Aerobic	1.1	Partially working	HH Connections- 15,500 Sewerage Lines- 20,443 Combine channel- 11Km
Sallaghari, Bhaktapur (Kathmandu Valley)	Aerated lagoon	2.4	Not working	Details not available
Hanumanghat, Bhaktapur, (Kathmandu Valley)	Oxidation Ditch	0.4	Not working	
Guheswori, Kathmandu (Kathmandu Valley)	Oxidation Ditch	16.4	Not working	Sewers- 6 Km Population Served- 53,000 Urban area- 21 Ha
Hetauda Industrial Estate, Hetauda	Oxidation Pond	1.1	Working	Industrial Wastewater Treatment Plant
Dhulikhel Hospital	Reed Bed (Constructed Wetland)	< 0.10	Working	Without Primary Treatment Bed Size- 261 m^2 Population served- 330
Kathmandu Municipality	Reed Bed (Constructed Wetland)	< 0.40	Working	No Primary Treatment Bed Size- 362 m^2 Population served- 330
Mulpi International School	Reed Bed (Constructed Wetland)	< 0.25	Working	No Primary Treatment Bed Size- 376 m^2 Population Served- 850
SKM Hospital	Reed Bed (Constructed Wetland)	0.15	Working	Bed Size- 141 m^2 Population Served- 500
Kathmandu University	Reed Bed (Constructed Wetland)	< 0.035	Working	No Primary Treatment Bed Size- 587 m^2 Population Served- 1300
Middle Marshyangdi Hydropower Project	Reed Bed (Constructed Wetland)	< 0.026	Working	No Primary Treatment Bed Size- 298 m^2 Population Served- 870
Pokhara Municipality	Reed Bed (Constructed Wetland)	< 0.115	Working	No Primary Treatment Bed Size- 3,308 m^2 Population Served- 3830
Kapan Monastery (Kathmandu Valley)	Reed Bed (Constructed Wetland)	< 0.015	Working	No Primary Treatment Bed Size- 150 m^2 Population Served- 300
Tansen Municipality	Reed Bed (Constructed Wetland)	< 0.030	Working	No Primary Treatment Bed Size- 583 m^2 Population Served- 1000
Sunga Community Wastewater Treatment Plant (Kathmandu Valley)	Reed Bed (Constructed Wetland)	50 m^3/day	Working	Community Wastewater Treatment Plant Bed Size- 150 m^2 Population Served- 1200

4. Wastewater Disposal and Use

In Nepal, the practice of wastewater use in agriculture and elsewhere and the emerging environmental and health consequences are not well documented despite the fact that the practice of wastewater irrigation is an age-old tradition that is intricately linked to the culture and livelihood system of the people of the Kathmandu valley. In the valley, in agricultural land located within city centres and urban fringes, farmers are known to practice wastewater irrigation in significantly larger areas (Rutkowski 2004). The practice of wastewater use in the Kathmandu valley is largely informal and there is no institutional regulation for wastewater use, at least for now. The farmers practicing wastewater irrigation use wastewater from different sources which include municipal sewage, rivers carrying wastewater and water stored in ponds and pools developed in the urban, peri-urban and rural areas of the Kathmandu valley.

4.1. Case Study of Khokana: Community-Based Wastewater Management System

This case study presents the success story of a community-based wastewater management system developed at Khokana, a dense medieval Newar settlement located in the Karyabinayak Municipality of the Lalitpur District. The traditional settlement of Khokana, which includes two settlements , the main Khokana village and small Khokana (*Sano Khokana*) covers only about 0.20 km^2. The community-based wastewater treatment system, described in this case study, is located in *Sano Khokana*, a small settlement serving a population of 229 people in 39 households. Farming is the main source of sustenance for the majority of households in the village. People in the village live in traditional clustered housing with a central courtyard and houses located around the courtyard, which is typical of traditional Newar settlements in the Kathmandu valley.

Households in *Sano Khokana* traditionally recovered solid waste and wastewater through a unique system of wastewater recycling and composting. In traditional Newar households, *Saaga* and *Nauga* had been used prior to the development of modern sewer lines and the use of flush pour latrines. *Saaga*, a pit of 3ft x 3ft x 2ft in size, was made by digging ground at one corner of the homestead and dumping all the biodegradable waste and wastewater produced in the homestead. Upon filling, it would be covered by hay and farm residues which would then get composted in 3-4 months' time for use in the agricultural fields. Excess water from *Saaga* was either used for irrigating small plots of vegetables within the homestead or directed to wastewater drains which would then be recycled for irrigation. *Nauga*, another pit made in the ground floor of the house was used as the urinating place, by digging the ground and putting a layer of ash on it. The people would urinate over the ash, which would get converted into useful fertilizer for use in the farms. These traditional practices of solid waste and wastewater management were unhygienic, unmanageable, odorous, and breeding grounds for house flies and other insects.

In 1981 the Ministry of Local Development, in collaboration with UNICEF, supported the construction of pit latrines in 31 households in *Sano Khokana* but only a few households actually used them and instead continued with their traditional practice of open defecation and waste management in *Saaga* and *Nauga* in the homestead. Since the practice of traditional waste management was unhygienic, people were susceptible to diseases of different kinds. The initiative of constructing pit latrines failed because of high groundwater table in the area. People feared that the latrines would get filled up quickly and require the frequent removal of sludge. Therefore, they connected the toilets directly to the surface drains which were not fully covered and were poorly maintained. This situation further intensified the problem of waste management in the village.

In 2007 Lumanti, a local NGO working for informal settlements, and UN-Habitat, working on water supply and sanitation issues in Asian cities for healthy living, joined together to help the community improve solid and liquid waste management in the village. The challenge was to develop a system for solid and liquid waste management that would be integrated and based on people's traditional practices, and therefore acceptable to them, offering a cost-effective and sustainable solution to the problem. Since almost 80% of households had toilets in the homestead, constructed with support from the Ministry of Local Development and UNICEF, and the disposal of black water from toilets was a problem in the absence of suitable septic tanks and/ or connections to appropriate sewerage systems, it was decided to develop a sewerage system connecting the toilets in each household to a centralized biogas digester. The development of the biogas digester was thought to be appropriate because it provided not only an alternative for sanitary handling of human excreta and grey water from households but also an opportunity to generate biogas for use by households besides recovering digested manure, which is readily suitable for use in the crop lands.

A Reed Bed Treatment System (RBTS) was integrated into the system so that effluent from the biogas digester and the wastewater generated by households could be treated and recovered for use on farms for irrigation. Maintaining suitable water content in the waste, fed into the biogas digester, was a prerequisite for the proper functioning of the biogas digester, so a system for diverting excess wastewater from the sewer line to RBTS was proposed. Thus, an integrated system with a biogas plant and RBTS was developed in the village, which included three essential elements that became bases for the success of the system:

i) An eco-sanitary system for the handling of solid and liquid waste that was based on proven technology,
ii) Inclusion of all households in the village into the system, offering them a sustainable solution to solid and liquid waste management,
iii) Resource recovery that drew upon the traditional practice of recovering solid waste and wastewater and an added value of benefit.

The biogas plant developed in *Sano Khokana* is a dome type anaerobic digester, 20 m^3 in capacity and designed for a retention time of 45 days. The system came into operation in August 2007 while the RBTS started functioning after a year, beginning in September 2008. The system has been in full operation benefitting 37 households in the village. The digested slurry from the biogas plant is directed to a slurry drying bed. Water from the slurry drying bed and excess wastewater from the sewer line is directed to the RBTS for treatment. The RBTS developed in Khokana is a horizontal flow system with the capacity to treat 18.5 m^3 of wastewater per day. The reed bed is 25 m in length, 9 m in width, and filled with a sand and gravel layer to a thickness of 70 cm. The wastewater diverted from the sewer line and wastewater coming from the slurry drying bed is passed through a three chamber anaerobic baffle reactor prior to entering the Reed Bed, which helps to improve efficiency in the operation of the system. Besides black water fed into the biogas digester, households also feed daily loads of biodegradable solid waste generated in the homestead into the biogas digester. The treated wastewater is collected in a small pond which is then directed for irrigation on the farm land.

The total cost of developing the system was NRs 1,300,000 (US $16,502), which was funded by UN-Habitat under the Water for Asian Cities Program. The direct beneficiaries of the biogas plant and RBTS are the 229 people in *Sano Khokana* from whom the operation and maintenance fund is collected. The operation and management of the system are carried out by a user group. The local community contributed 3,500 ft2 (325.16 m^2) of land for infrastructure development, the market value of which is currently NRs 3,000,000 (US $38,086). At present each household whose latrine is connected to the system pays a monthly fee of NRs 30 (US $0.38) for wastewater and sewage disposal. The five households that benefit from the biogas plant each pay NRs 200 (USD $2.54) per month. The collected fund is deposited in the account of the user group and is used to pay for the salary of the caretaker of the biogas plant and RBTS and also for the repair and maintenance of the system. The caretaker of the system is a lady from the village who is paid NRs 1,500 (US $19.04) per month. She is responsible for the day-to-day operation and maintenance of the biogas plant and the collection of daily loads of solid waste from households to feed into the digester.

The development of the integrated wastewater management system has tremendously improved the environment and sanitation in Sano Khokana. This has added to the dignity of the people as the village is now declared an open defection free village. The system has eliminated the burden for emptying the filled septic tanks, at least once a year, which not only led to cost savings for emptying the septic tank but also reduced the drudgery involved in the process. The system is also designed to handle other household and kitchen waste, fed into the biogas plant, which has improved the cleanliness of the homestead area. The gas generated in the biogas digester is distributed to five households whose energy needs for cooking are almost fully met with the gas supply throughout the year. The good quality manure, with high fertilizer value, generated from the biogas plan is an additional benefit to the people. The treated water coming out of the RBTS, which is full of nutrients, is stored in a pond and then recycled for irrigation. This element of resource recovery built into the system has been an additional benefit to the people. The wastewater that used to be discharged haphazardly prior to the development of the system is now recovered for productive uses. According to the hygiene assessment of the village carried out by Lumanti in 2009, the occurrence of diseases caused by poor sanitation was found to have been reduced by almost 90%.

There are seven community wastewater irrigation systems in one small area of Khokana with the size of the irrigated area under each system as small as 0.26 to 7.76 ha (Table 3). The most noticeable observation is the almost total dependence on wastewater for irrigation during the dry season when other sources of water were not available for irrigation. The wastewater in the dry season in the study area was found to be used for the production of vegetables, which is an important source of cash income for people in the area.

The high nutrient content of the wastewater was also considered by farmers to contribute positively to crop production. In an attempt to analyse the nutrient content of wastewater, the average nitrate content in wastewater was 6.95 mg/l, 4.9 mg/l, and 3.5 mg/l respectively in Saaga, in the conveyance channel, and in the wastewater storage ponds. Similarly, the concentrations of phosphorus and potash at the three stages were 3 mg/l, 10.7 mg/l and 4.35 mg/l, and 42.9 mg/l, 149 mg/l and 27.7 mg/l, respectively. These nutrients, which are present in wastewater, are needed by the crops for their growth, development, and production.

4.2. Use of Wastewater from the Hanumante River in the Bhaktapur District

There is a study of the practice of using wastewater from Hanumante River in Bhaktapur, which is a tributary of Bagmati River. The study involved the documentation of wastewater use practices in 55 farming households in the area that are essentially small farmers with an average landholding size of 0.23 ha. The Hanumante River is the major stream in the areas passing through the urban core of the city of Bhaqktapur. The river carries domestic and industrial wastewater generated in the urban areas of Bhaktaur and Madhyapur-Thimi and also the river reach is used for solid waste dumping. The water quality analysis of the river at seven locations from upstream to downstream is provided in Table 4, which

Table 3: Irrigation Coverage from Wastewater in Selected Community Wastewater Management Systems in Khokana

S.N.	NAME OF SYSTEM	LOCATION			IRRIGATION COVERAGE			SUPPLEMENTARY IRRIGATION SOURCE
		Ward No.	Name of the System	No. of Hhs	Total Area (ropani)	Coverage in the Wet Season	Coverage in the Dry Season	
1	Nhaya Bhu Tacha Dha	1	Nhaya Bhu	30	25	All	60%	None
2	Duney Chey Chuke Dha	1	Dhuney Chey, Nhaya Bhu	40	50	All	75%	None
3	Lee Dha	2 3	Taa Jhaya Kalnani, Gaa Bhu	60 35	80	All	80%	Gaa Phuku
4	Ghashi Dha	4 5	Thala Chey Kway Lacchi, Kutu Phuku	55 50	150	All	75%	Kutu Phuku
5	Gha Dha	6	Nyah La, Nanicha	65	70	All	75%	None
6	Nani Chukye Dha	6	Nanicha	6	5	All	75%	None
7	Dhokashi Dha	7 8	Kway lachhi Dhokashi	40 20	20	All	50%	Fanga Phuku
	Total			**401**	**445**			

1 ha= 19.46 ropani,

clearly shows that organic waste in the river are a major contributor to water quality degradation. Also, the large concentration of faecal coliform in the river water is indicative that any direct use of river water, including irrigation, would be hazardous to human health.

It is noted that as many as 64% of the farming households are using wastewater from the Hanumante River for irrigation throughout the year while 34% of the them are using water for irrigation only during the monsoon. As many as 62% of the farmers owned a pump to lift water from the river for irrigation. The wastewater in the area is shown to be used in irrigating vegetables, which is an important means of cash income for farmers in the area. The farmers sell their produces in the adjoining markets of Thimi, Bhaktapur and in Kathmandu. The farmers indicated increasing problems in selling their vegetables that are produced using wastewater. As many as 67% of the farmers indicated that the buyers restrain from buying vegetables produced in the area around the Hanumante River because of the prevailing practice of wastewater use in vegetable production. On the other hand, 33 % of the farmers indicated that they did not face any difficulty in selling the produce to consumers even though the consumers knew that the vegetables are produced using wastewater.

The perception of famers practicing wastewater irrigation in terms of the effects of wastewater use in crop production was also studied. While only 20% of farmers reported an increase in the productivity of the crops with the use of wastewater, as many as 80% of the farmers noticed a reduction in crop productivity with wastewater application. Those farmers who saw a decrease in crop productivity due to wastewater use attributed this reduction to the high nutrient content in the wastewater. Farmers in the area have noticed the drying and wilting of crops with the repeated application of wastewater.

The traditional wastewater management practice in the Kathmandu valley and also in other parts of the country has been declining rapidly due to changing socio-economic conditions of the people and increasing awareness and consciousness of the people to health and hygiene. The practice of developing *Saagah* in the backyard of the house in the Newar settlement has almost totally been eliminated except in some traditional Newar households in rural areas. People have increasing preferences for connecting their toilets and wastewater system to sewer lines. This change in practice has led to the direct disposal of grey and black water in rivers and open water bodies, which has been

Table 4: Variation in the Water Quality of Hanumante River Water Used for Irrigation by Farmers

S.N	Parameters	Unit	Sample ID							NWQS for Irrigation
			1	2	3	4	5	6	7	
1	pH	-	7.68	7.36	6.97	6.99	7.03	7.06	7.19	6.5-8.5
2	E.C	uS/cm	126	148	423	454	434	423	392	< 40ms/m
3	DO	mg/L	7	5.3	0	0	0.8	1.5	0.7	
4	Calcium	mg/L	9.6	15.2	39.2	44.8	46.4	40	42.4	
5	Magnesium	mg/L	2.91	4.86	13.1	0.97	7.29	2.43	5.34	
6	Chloride	mg/L	7	7	29	29	28	26	23	< 100
7	TSS	mg/L	5	75	65	56	98	31	36	
8	VSS	mg/L	11	18	50	47	33	27	20	
9	Total Solids	mg/L	169	206	234	318	318	270	254	
10	BOD	mg/L	3.5	4.7	79.9	67.4	28.9	25.9	18.9	
11	COD	mg/L	18.9	17.9	128	123	73.7	61.4	41.5	
12	Ammonia	mg/L	0.4	2.6	21.6	25.1	17.8	15	11.5	
13	Nitrate	mg/L	3.39	2.02	0.81	0.81	0.91	0.41	<0.2	
14	Total Phosphorus	mg/L	0.09	0.17	1.3	1.58	1.71	1.16	0.82	
15	Sodium	mg/L	8.07	9.23	22.9	26.5	23.8	22.0	19.1	< 70 mg/l
16	Potassium	mg/L	3.52	4.11	15.6	16.9	14.9	14.1	9.49	
17	Chromium	mg/L	<0.02	<0.02	0.02	<0.02	<0.02	<0.02	<0.02	<0.1 mg/l
18	Lead	mg/L	<0.01	<0.01	<0.01	<0.02	<0.02	<0.02	<0.02	<0.2 mg/l
19	Zinc	mg/L	0.05	0.09	0.21	0.1	0.05	0.13	0.07	<1.0 mg/l
20	Faecal Coliform	CFU /100 ml	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	TNTC	<1 count /100ml

Note: 1-7 locations of water sampling upstream to downstream on the river course NWQS- Nepal Water Quality Standard (Source: Sada 2010) responsible for increasing pollution loads in the river and other water bodies. It has been observed that the practice of using wastewater in agriculture at present is limited to the older generations while young boys and girls restrain from handling wastewater. Nevertheless, farmers practicing wastewater irrigation feel that with the change in the practice of wastewater for irrigation purposes, they have been losing valuable nutrients that were being recovered and used on crop lands.

5. Policies and Institutional Set-Up for Wastewater Management

5.1 Policies and Legislation

In the absence of a separate policy for wastewater management, the related issues of wastewater management are dealt with under sectoral policies and strategies relating to water supply and sanitation. Two documents that reflect upon the national commitment to improve water supply and sanitation in the country are the Rural Water Supply and Sanitation Sector Strategy (2004) and the Urban Water Supply and Sanitation Policy (2009). The Rural Water Supply and Sanitation Sector Strategy (2004) is based on a national commitment to total water supply and sanitation coverage in the country as envisaged in the Millennium Development Goal. The Urban Water Supply and Sanitation Policy (2009) envisions an improvement in water service delivery in urban areas, including an improvement in the wastewater systems and services, the promotion of public-private partnerships in the development of infrastructure and services, and the enforcement of national guidelines for the safe disposal and use of wastewater. In an attempt to improve water supply and sanitation services, National Guidelines for Hygiene and Sanitation Promotion (2005) have been endorsed, emphasising:

- Increasing coordination among agencies related to water supply and sanitation with the active role of the National Drinking Water and Sanitation Committee at the central level,
- Encouraging the effective participation of non-governmental organisations and the private sector in increasing water supply and sanitation coverage,
- Developing sewerage systems with treatment plants with the active involvement of consumer groups,
- Prohibiting the direct disposal of untreated sewage into water bodies.

The legislation and regulatory provisions encompassing the issues relating to wastewater management and safeguarding water bodies include: the Environmental Protection Act (1996), Local Self-Governance Act (1999), Industrial Enterprises Act (1993), National Wetland Policy Act (2003), National Sanitation Act (1994), Pesticide Act (1992), Solid Waste Management and Resource Mobilisation Act (1988), and Water Resources Act (1992).

Solid Waste Management and Resources Mobilisation Act (1988): This act focuses on solid waste management in the Kathmandu, Bhaktapur and Lalitpur municipalities. The act lays out regulatory provisions for the implementation of activities and the mobilisation of resources for solid waste management in the stated areas. The act sets out provisions for the collection, handling and disposal of solid waste in such a way that it does not cause environmental damage in the area designated for the disposal of solid waste. The roles and responsibilities of the citizen relating to the collection and disposal of solid waste have been identified and set by the act.

5.2 Institutional Arrangements for Wastewater Management

The Ministry of Water Supply and Sanitation (MWSS) has overall responsibility for making policies and development plans and administering water supply, sanitation, the transport sector and related physical infrastructure development in the country. The Ministry has established a Sanitation Division responsible for providing technical assistance to bilateral and multilateral organisations in formulating, monitoring and evaluating sanitation programmes, including urban and rural rainwater and domestic sewerage, except the road drainage system.

The Department of Water Supply and Sewerage (DWSS) under MPPW is responsible for the planning and development of water supply and sanitation systems and related infrastructure development in the country. The responsibilities of DWSS encompass rural and small urban centres in the country. The Nepal Water Supply Corporation (NWSC) has been created as a semi-autonomous corporation responsible for water supply and sewerage in major urban centres outside the Kathmandu valley. In the Kathmandu valley, responsibility for the development, operation and management of infrastructure and services for water supply and sewerage system lies with Kathmandu Upatyaka Khanepani Limited (KUKL), an institution created under a public-private partnership. The Local Self Governance Act (1999) sets out the duties of local government, municipalities and VDCs with regard to drinking water, irrigation, sanitation, and water conservation. The main role of local governments is expected to be the development of water and sanitation facilities by drawing up local plans and programmes, and also providing materials and financial support for the development of infrastructure and services by the local community.

5.3 Regulation of Wastewater Use in Agriculture and Other Uses

The regulations relating to wastewater use in agriculture and other uses are weak in the absence of necessary regulatory provisions and the absence of institutions with autonomous responsibility for wastewater use and management. There is no effluent quality specified for the disposal of wastewater in the water bodies, but the quality criteria generally reported by most agencies for different water uses is provided in Table 5. In 2008 quality guidelines for the safe use of wastewater in agriculture, aquaculture, animal watering, recreation, and the environment were formulated and published in the Gazette of the Government of Nepal (Sada 2011).

There is no institutional arrangement to regulate wastewater use in agriculture and also there are no guidelines available to ensure the safe handling of wastewater and agricultural produces. Considering that wastewater use in agriculture would accelerate in the country in the future, at least in urban areas like Kathmandu, developing wastewater irrigation guidelines would be a crucial first step to addressing wastewater use in agriculture.

Table 5: Water Quality Standards for Different Uses Reported by Water Agencies in Nepal

Parameter	Drinking	Aquatic life	Bathing	Agriculture
pH	6.5-9.2	6.5-8.5	6.5-9	6.5-9
TDS (mg/l)	1500	1000	1500	500-3000
SS (mg/l)	-	25	50	-
DO as O2 (mg/l)	-	6	3	3
Cl as Cl (mg/l)	600	500	1000	100-1000
SO4 as SO4	400	500	1000	1000
NO3-N as N (mg/l)	-	20	20	25
NO2-N as N (mg/l)	-	0.15	1.0	1.0
NH3-N as N (mg/l)	-	0.02	0.2	0.2
Total PO4 as PO4 (mg/l)	0.1	0.1	0.2	0.2
BOD as O2 (mg/l)	4	4	6	10
F as F (mg/l)	3	1	1.5	1.5
Total Hg	-	0.0001	0.001	0.001
Total Cd	-	0.005	0.005	0.01
Total Pb	0.05	0.05	0.05	0.1
Cr	-	0.05	0.05	0.1
Phenol	0.002	0.005	0.1	0.2
Total Cyanide	-	0.005	0.2	0.2
Total Colliform (MPN/100ml)	-	-	1000	1000

Source: Sharma et al. 2005

6. Research on Wastewater Systems and Use

Research and knowledge development and the dissemination of pertinent knowledge on wastewater management are highly scattered and non-systematic in Nepal. The research efforts are limited to a small number of educational and research institutions and development organisations and the professionals engaged therein whose areas of involvement have been as stated below:

- Analysis of the state of water quality degradation in the surface water bodies (rivers, lakes and ponds) including limnological studies in the surface water bodies.
- Assessment of the performance of technology and infrastructure relating to wastewater management.
- Health and livelihood consequences and disease dynamics emerging from water quality degradation.
- Interdisciplinary analysis of processes and outcome of the degradation of surface and groundwater systems.
- Technology options for decentralised wastewater treatment.
- Policy research on surface and groundwater use and management.

The organisations occasionally involved in research and knowledge development for wastewater systems include universities, research organisations and units in the government ministries and departments with an independent responsibility for research and development, and a small number of development organisations involved in development and policy research. These include:

- Central Department of Geography, Tribhuvan University
- Institute of Engineering, Tribhuvan University
- Kathmandu University
- Nepal Engineering College, Pokhara University
- International Centre for Integrated Mountain Development (ICIMOD)
- Environment and Public Health Organization (ENPHO)
- Institute of Social and Environmental Transition-Nepal (ISET-Nepal)
- Nepal Agricultural Research Council
- System Management and Training Programme (SMTP), Department of Irrigation

- Nepal Health Research Council, Ministry of Health

Some of the key achievements in research and knowledge development for wastewater systems and management in Nepal to date are as follows:

- Systematic analysis of water quality in the rivers of the Kathmandu Valley carried out by the Department of Hydrology and Meteorology (DHM), Government of Nepal, and ENPHO during 1992-1996
- Classification of River Systems in the Hindu-Kush Himalayan Region carried out by ICIMOD during 2006-2007 based on water quality criteria which also included rivers in the Kathmandu Valley
- Kathmandu Valley Environmental Outlook prepared by the Ministry of Environment Science and Technology in support of ICIMOD and UNEP in 2007
- Design Optimisation and Promotion of Decentralised Wastewater Management System in Nepal by ENPHO

No research projects specifically focusing on wastewater use and management that looks into social, economic, technological, environmental, health, and livelihood concerns are known to be underway in the country.

7. Knowledge Gaps and Needs for Safe Wastewater Use

No analysis is available to date on the state of knowledge and knowledge gap regarding safe wastewater use across different water sector agencies and their personnel in the country. This lack of emphasis on assessing the knowledge gap in terms of safe wastewater use is probably due to the existing perception of considering wastewater an environmental 'nuisance' and not a 'resource' by the water sector agencies and their personnel. Much of the emphasis to date has been on the development of physical infrastructure and services in the collection, conveyance, treatment, and safe disposal of wastewater whereas the recycling and reuse of wastewater have received little emphasis in the design and implementation of development programmes. Part of the reason for not considering wastewater as a potential resource for productive use in agriculture and other sectors has been the lack of institutional coordination across water sector agencies. Water sector development in the country is highly sectoral, with sectoral policies dominating the development of water systems and services in each sector.

In the course of preparing this case, relevant government ministries and departments and their personnel working in policy and key decision-making positions were contacted and their views on the relevance, state, and requirement of knowledge on wastewater management and safe wastewater use in their day-to-day engagements in delivering the services were assessed. The information provided below is based primarily on this survey, which was undertaken in a very short period of time. The personnel in the government agencies identified gaps on two levels: i) gaps in internalising and the safe use of wastewater as an institutional agenda of the agencies, and ii) gaps in programme planning and implementation.

The gaps in internalising the safe use of wastewater as a regular programme agenda stems essentially from the lack of an initiative on the part of the water sector agencies in considering the possibility of wastewater use as an aspect of their water development programmes. The Water Resources Strategy endorsed by the Government of Nepal in 2002 envisions an integrated approach to water resource development, whereby exploring the possibility of wastewater recycling/use has been identified as one of the alternatives to approaching/enhancing water security, at least in areas known to face water scarcity. There have also been, in general, adequate regulatory provisions and legislation to promote the safe use of wastewater. Water quality standards for the safe use of wastewater in agriculture, aquaculture, livestock watering, recreation, and environmental uses, published in the Gazette of the Government of Nepal in 2008, enforces the national commitment to the promote safe use of wastewater. However, the emphasis on translating the policy emphasis into actual plans and programmes for safe wastewater use has been largely lacking in most water sector development agencies and also those concerned with health and environmental issues.

The gaps identified in the programme planning and implementation by relevant water sector agencies, as revealed by their key personnel, is presented in Table 6. While the personnel in most water sector agencies and those relating to health and the environment revealed a high level of relevance and the importance of knowledge of safe wastewater use, they also invariably identified a low level of current emphasis on developing programmes and plans in promoting the safe use of wastewater. All of the agencies also identified a high level of need in developing institutional capacity, in terms of the development and addition of human, materials and technology resources for their enhanced roles in the promotion of knowledge and practices regarding safe wastewater use.

Table 6: Gaps in Programme Planning and Implementation Relating to Safe Wastewater Use across Selected Water Sector Agencies

Levels of Gaps	MOA &C	MOP-PW	MOH	MOE	DOI	NARC
Relevance of Knowledge of the Safe Use of Wastewater	High	High	High	High	High	High
Sectoral Policy Emphasising/Encompassing Wastewater Issue	NE	Adequate	Adequate	Adequate	NE	NE
Resources (Material, Technology, and Human Resources) to Address Safe Wastewater Use	Low	Medium	Low	Low	Low	Low
Programmes/Plans Promoting Safe Wastewater Use	Low	Low	Low	Low	Low	Low
Need for Institutional Capacity Building on Safe Wastewater Use	High	High	High	High	High	High

NE: Non existent

8. Concluding Remarks

This case sought to present the state of waste water production and usage in the context of the Kathmandu valley and the existing policy guidelines and regulatory frameworks regarding safe wastewater use in the country. The last section of the case looked into the knowledge gap and the need for capacity building among farmers using the water, water sector agencies and their personnel regarding the safe use of wastewater in the country. This also attempted to draw on micro-level perspectives, especially the traditional practices of wastewater use in the Kathmandu valley, and therefore the need for the promotion of knowledge and practices for safe wastewater use management. The following conclusions emerge based on the contents and analysis of this case:

- Wastewater management and use in the Kathmandu valley were noted to be an age-old practice, intricately linked to the traditional knowledge and wisdom of the people. Traditionally wastewater is considered a 'resource' by the people while the development efforts of water sector agencies relating to wastewater management have been essentially guided by the notion of considering wastewater a 'nuisance' and a key contributor to environmental pollution. This notion was found in sectoral and disciplinary perspectives in water system development, which is essentially guided by a technological solution to all water problems.
- Wastewater production in the Kathmandu valley was noted to have increased significantly since 1970, especially in urban areas, due to the accelerated increase in population, unplanned and haphazard development of infrastructure and services for water supply, sanitation, and wastewater management. The analysis also clearly revealed that the pace of development of infrastructure and services for wastewater management has been largely inadequate and incomplete to meet the needs. Also, a centralised and technology-based solution to wastewater management was shown to have failed in addressing the wastewater problem, especially in the urban areas of the Kathmandu valley.
- The analysis noted a commitment at the policy level in addressing the problem of wastewater management in the country. The existing legislation and regulatory provisions were also noted to be generally adequate to address the problems of wastewater management. On the other hand, gaps were identified at the level of implementing policies, legislation and regulatory provisions relating to the safe use of wastewater. Gaps were also noted at the level of institutional development and in internalising the problem of wastewater management as an important area of development intervention by water sector agencies.
- The analysis noted a lack of emphasis on research and development in the country in improving the state of knowledge, practices, and solutions to wastewater management. There are only a small number of agencies and their personnel who have a limited level of engagement with research and development into wastewater use and management. This has been essentially due to the lack of national emphasis on the promotion of wastewater use.
- The key conclusion emerging from the analysis is the need for considering safe wastewater use as an important area of water sector development in the country. There are visible water stresses, especially in urban areas, emerging from dry season water uncertainty, groundwater depletion, and climatic variability. There is an established potential of promoting wastewater use as a means of addressing water uncertainty and approaching water security at a local level. Considering emerging concerns on climate-induced water uncertainty in the country, especially concerns about the likely depletion of water resources due to climate change, there is a clear potential for considering safe wastewater use to be an important method of preparedness and adaptive strategies for possible future water security.

References

ADB & GON. 2010. "Kathmandu Valley Water Supply and Wastewater System Improvement: Project Feasibility Study Final Report." Manila, the Philippines: Asian Development Bank (ADB).

A.K. Shukla, U.R. Timilsina, and B.C. Jha. 2012. "Nepal Country Paper, Wastewater Production, Treatment, and Use in Nepal."

Basnyat BB. 1999. "Fertilisers and the Environment in the Context of Nepal: How Big is the Problem?" Paper presented in the Workshop on *Present Environmental Challenges and Management of Pesticides, Chemical Fertilizers and Solid Wastes*, Kathmandu, Nepal, October, 3-4.

CBS. 1995. "A Compendium of Environmental Statistics of Nepal." Ramshahpath, Kathmandu: Central Bureau of Statistics (CBS).

CBS. 2011. "Preliminary Results of National Population Census 2011." Ramshahpath, Kathmandu: Central Bureau of Statistics (CBS).

FAO. 2012. "Aquastat." Accessed May12. www.fao.org/nr/water/aquastat/data/query/results.html.

ICIMOD, MOEST/GON and UNEP. 2007. "Kathmandu Valley Environmental Outlook." International Center for Integrated Mountain Development (ICIMOD), Ministry of Environment Science and Technology of Government of Nepal (MOEST/GON) and United Nations Environmental Program (UNEP).

Mool PK, Bajracharya SR and Joshi SP. 2001. "Glacial Lakes and Glacial Lake Outburst Flood Events in the Hindu Kush-Himalayan Region." In *Global Change and Himalayan Mountains*, edited by Shrestha KL. Lalitpur, Nepal: Institute for Development and Innovation.

NPC. 2010. "Millennium Development Goal Needs Assessment for Nepal." National Planning Commission (NPC) and UNDP.

Nyachhyon BL. 2006. "Service Enhancement and Development of Sanitary Sewerage System in Urban and Semi-Urban Settings of Nepal." *Economic Policy Network*, Policy Paper No. 23. Ministry of Finance, Government of Nepal and Asian Development Bank.

Palikhe BR. 1999. "Pesticide Management in Nepal: Implementation Issues and Experiences." Paper presented at a workshop on *Present Environmental Challenges and Management of Pesticides, Chemical Fertilizer and Solid Waste*, October 3-4, Kathmandu, organised by Society for Environmental Journalists, Nepal.

Ruthkowski T. 2004. "Study of Wastewater Irrigation in Kathmandu Valley." *Water Nepal*, 11-2:63-71.

Sada R. 2010. "Processes and Consequences of Degradation of Hanumante River." Unpublished M.Sc. Thesis. Pokhara University, Nepal.

Sharma S, Bajracharya RM, Sitaula B K and Merz J. 2005. "Water Quality in the Central Himalaya." *Current Science*, 89-5:774-786.

Shrestha J. 2011. "Traditional Practices and Knowledge System in Integrated Wastewater Management in Kathmandu Valley." Unpublished M.Sc. Thesis. Pokhara University, Nepal.

UNDP. 2006. "Human Development Report- Beyond Scarcity: Power, Poverty and Global Water Crisis."

WECS. 2003. "Water Resource Strategy Nepal." Water and Energy Commission Secretariat (WECS), Government of Nepal.

UNEP. 2001. "Nepal: State of the Environment 2001." Kathmandu, Nepal: United Nations Environment Program (UNEP) and International Centre for Integrated Mountain Development (ICIMOD).

WECS. 2010. "Concept Paper on Eco-Efficient Water Infrastructure Policy in Nepal." Water and Energy Commission Secretariat, Government of Nepal.

CASE 14

Wastewater Reuse in Mendoza Province, Argentina (Argentina)

Carlos Horacio Foresi [1]

Abstract

In Mendoza Province, Argentina, treated wastewater has been reused in agriculture for more than five decades. Factors driving the demand for this resource for irrigation in this region are the infrequent rainfall and aridity typical of a desert.

Situated in central-western Argentina, in the foothills of the Andes, Mendoza records an average annual rainfall ranging from 200 mm to 250 mm depending on the latitude. All human activity and production is concentrated on just 3.5 per cent of its surface area, which covers 148,827 km^2, and around four man-made oases that exploit water from the region's rivers. There is a total of more than 500,000 cultivated hectares where intensive agriculture takes place, the main crop being grapevines for wine-making, followed by olive trees, stone and seed fruit, vegetables, forestry and fodder.

In this context, water resources are in high demand from farmers, especially considering that treated wastewater comes with guarantees regarding quality control and the way it is used, to ensure against unwanted effects on the soil or crops. Moreover, with this practice the water is treated in effluent purification plants and nutrients are added

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to the soil, bringing an economic advantage which takes on greater significance in an arid area. However, what is needed in order to optimise this are the necessary conditions and expertise to maintain the soil's fertility (organic, mineral and hydrogeological conditions) and to obtain products that meet the health and hygiene standards required by their place of destination, as well as ensuring preservation of the environment, all of which are necessary for wastewater to be used in a controlled manner. To this end, the General Department of Irrigation in 2003 issued Resolution No. 400/03 of the Honourable Administrative Tribunal, establishing mandatory regulations for designated ACREs (Specialised Restricted Cultivation Areas).

A significant percentage of the purification facilities in the province currently provide treated effluents in an ACRE. In terms of surface area, approximately 7,000 ha are irrigated with wastewater in the summer and, consistent with population density, are concentrated mainly on the northern oasis. Eighty-five per cent of this surface area is regularised by law and is managed by its users, with controls from the General Department of Irrigation. What remains is the important task of also regularising winter reuse. In 2006 guidelines and requirements for this are set out in Resolution No. 500/06 of the Honourable Administrative Tribunal.

Keywords: agricultural reuse, ACRE, wastewater, irrigation

1. Introduction

An entire case is devoted to the General Department of Irrigation in section VI of the Constitution of Mendoza, which has been in force since 1916. This body's mission is to manage and protect all available surface and groundwater resources in the province, taking into consideration its various uses: drinking, irrigation, industry, energy, and recreation. Within its uses, the reuse of treated wastewater in agriculture has become more clearly defined since the creation in 2012 of the Water Reuse Department (*Departamento Reusos Hídricos*), whose primary purpose is the technical and administrative regularisation of ACREs. The General Department of Irrigation is an independent body that has independence for managing its own resources and is not financially dependent on budget allocations from the Honourable Legislature or their implementation by the Executive Office. Moreover, the General Department of Irrigation has administrative autonomy and manages water in Mendoza Province. Its main function in Mendoza is the general management of public water resources and it is also responsible for handling all matters related to water resource management, and the protection, distribution and regulation of water in natural and artificial waterways. This institution has various roots in government and civil society organisations and stems from colonial times. The General Department of Irrigation, as we know it today, came into being in 1884 with the passing of the General Water Act, stating: "The management of water and the general fulfilment of this act will be under the direction of the General Department of Water". Ten years later, in 1894, the Constitution of Mendoza Province renamed the General Department of Water as the General Department of Irrigation, the name it still goes by today.

The feature of wastewater management in Mendoza that stands out is that it is carried out together with users' organisations called Waterways Inspectorates (*Inspecciones de Cauces*)[i] which, whilst having functional dependency on the General Department of Irrigation, are governed by a specific law i.e. "Law 6405" decreed by the Honourable Legislature of Mendoza in 18 July 1996.

It has already been said that agriculture in arid and semi-arid areas such as Mendoza Province, depends almost exclusively on irrigation. The demand for water for irrigation represents more than 80 per cent of the total need for water. Likewise, continuing population growth also means an increase in the demand for water, which adds to the pressure of making sure that this resource is distributed properly. This means that it is crucial to use this resource more efficiently, even more so when we consider the drop in snowfall seen in recent years.

An available alternative that could lessen the strain on water resources is the reuse of treated urban effluents in agriculture. While this practice has been in development for more than 50 years in our province, it has only been regulated since 2003. This study provides a description and analysis of the situation regarding the reuse of water in agriculture in the province to serve as a basis for decision-making by the various stakeholders involved.

2. Brief Historical Overview

2.1. Campo Espejo ACRE

The first sewage networks were installed in the capital of Mendoza Province in the 1920s. The untreated liquids were carried by gravity pipelines to a state-owned uncultivated field situated several kilometres north of the city. People started to call this field 'Campo Espejo' (Mirror Field), almost certainly because of the brilliant shine, caused by deposited effluents, which could be seen from far away. Soon after, established farmers in the vicinity built unstable waterways to divert these liquids and irrigate crops.

Many years passed before the first primary treatment plant was built (1976) by the company that provided drinking water and sewage services at the time, Obras Sanitarias de la Nación (OSN). This plant was later remodelled and extended but this did not succeed in reversing the risk posed by using liquids with this level of treatment for irrigation. In 1994, a *Unión Transitoria de Empresas privadas (UTE)*[ii] won the contract to build a new plant. The project to build waste stabilisation ponds would be carried out in accordance with the WHO standards for secondary treatment. Twelve sets of three ponds were constructed, with the UTE's 20 year contract to treat the waste liquid for a period of 20 years in mind. The conditions are now being reconsidered because the terms of the contract have expired. Waters have been established below an ACRE which today covers a surface area of 3,000 hectares.

2.2. Paramillo ACRE

At the beginning of the 1980s, another large sewage treatment plant was built to collect water from Greater Mendoza. A set of four large ponds at a site situated some 30 kilometres to the east of the Campo Espejo allowed the liquids to be properly purified and a new ACRE to be developed in the surrounding area. This place, as its name (which comes from *páramo*, meaning wasteland) suggests, really was a barren wilderness given that no crops grew there due to a lack of rights or irrigation systems. Today, thanks to the organised utilisation of treated sewage and groundwater, Paramillo has undergone a transformation. It should perhaps be renamed, given the remarkable nature of the transformation including thriving high-tech farms that provide work for hundreds of people in the 3,500 hectares of land that make up the ACRE.

3. Factors that Have Influenced the Successful Development of Wastewater Reuse in Mendoza

3.1. Demand

Reference has already been made to the arid conditions of the province. In order for any crops to grow in Mendoza, irrigation must be used to supplement the lack of rainfall. Faced with this situation, farmers are always alert to sources that may be of use to them, whether it be surface water from rivers or streams, groundwater, or reused water.

There is a great deal of interest in treated sewage because, as well as being available throughout the year in areas that do not have registered irrigation rights, it brings with it nutrients and organic matter that in turn reduce the costs of the fertilization that is so necessary for skeletal and mineral soils like those found in Mendoza. This is most certainly a determining factor but this interest is also, of course, closely tied to the quality of the water resource as farmers are not willing to accept just any water. The quality of the treated sewage is acceptable at the current level of treatment, but not for unrestricted irrigation.

3.2. Management of Water Reuse by Waterways Inspectorates

It has already been stated that the Waterways Inspectorates are the authorities in charge of applying the Water Act 1884 and are responsible for policing minor waterways.

They are also involved in the technical and administrative management of the ACREs that are irrigated with wastewater; added to its specific functions are some aspects that are regulated in Resolution 400/03 and that deal with operational matters.

This success has had and continues to have great bearing on the sustainability of the ACREs given a strong normative framework, on the one hand, and the continuity of more than a century of practice and carrying out its functions.

The Waterways Inspectorates have three basic pillars that underpin its continuity:

- Self-sufficiency and administrative autonomy: as they determine and implement their own budgets. The Users' Assembly of the Waterways Inspectorate meets twice a year: once in November to determine the budget for inspection costs and the pro rata amount that users are to contribute to pay for them the following year; and again in May to approve the budget accounts drawn up by the Waterways Inspectorate from the previous financial year. The Waterways Inspector manages the finances of the inspection. All of this is done under the legal control of the General Department of Irrigation as a higher water authority.
- Direct and representative democracy: users have the power to select the authorities of their canals. This system is a feature of the nature of the consortium reviewed by waterways inspectorates. Under this system, every four years the users elect by secret and mandatory vote those who will fill the role of administrator and legal representative of the consortium through the Waterways Inspector. But, notwithstanding the democratic election of this representative, the Users' Assembly can also deal with important aspects of the inspection.
- Monitoring by higher authorities: as the previous point shows, the Waterways Inspectorate is subject to monitoring by the General Department of Irrigation. This monitoring, in the context of the self-sufficient relationship, is limited to the legality of the performance of the Inspection. This is provided for in article 23 of Law 6405, which lays out oversight duties via the Honourable Administrative Tribunal of the General Department of Irrigation: approve the statutes of the inspectorate organisations; request books and documents to be shown as it deems necessary; solicit reports and arrange investigations ex officio or on request; verify that mandatory precautions are fulfilled when appointing authorities; appoint watchdogs for the Users' General Assembly (ex officio or at the request of the users when there are reasons serious enough to justify this) and the Superintendence (monitor the fulfilment of the responsibilities, duties and functions assigned to the Inspectorate and Associations, taking care not to disrupt the consistency of their respective management by the legitimately constituted authorities).

The Waterways Inspectorate of the Specialised Restricted Cultivation Areas (ACREs), notwithstanding the other legal powers, should ensure the proper distribution and use of reuse water, making sure that it is carried out within the perimeter of the ACRE. It should also check that regulations are observed in connection with the authorised crops and all activity associated with them.

The inspectorate should also use the regulatory framework to monitor the quality and volume of water distributed at the overflow point from the purification plant to the ACRE before being reused. Every year, the Waterways Inspectorate that oversees the technical and administrative management of the ACRE should ask farmers to provide a sworn statement of the crops they are going to grow in their fields and inspect them at random to check on this. When crops are not authorised, to ensure that they stop growing them, they issue a warning to initiate administrative action consisting of, firstly, a warning, then a fine, which may lead to closure of the water source (irrigation turns or boreholes). Although this is the intended sanctions system, there have been no cases where it has been applied, but this could be due to the inaction of the Waterways Inspectorates.

3.3. Works and Coordination

As is already known, for the reuse of water in agriculture to be sustainable over time, specific work must be carried out with regard to the purification of liquids, such as in the area where water is reused (ACRE), that ensures water quality, efficiency and monitoring of its use. In Mendoza, sewage is treated by a decentralised government company, Agua y Saneamiento Mendoza S.A. (AySAM SA), and irrigation is managed by another organisation, the General Department of Irrigation, which operates the irrigation system through the corresponding Waterways Inspectorates. The crucial relationship between the two entities has not always been properly coordinated, neither has there been an agreed criterion for assigning funds to carry out works. Consequently, there are shortcomings in the maintenance of the plants and, furthermore, plans for future expansion are made difficult by continuous population growth.

4. Reuse of Treated Sewage in Mendoza

The total volume of water treated in all of the purification plants in Mendoza is, on average, approximately 5 m^3/s. The current population of the province is around 1,800,000 inhabitants (according to the 2010 national census it was 1,741,610 inhabitants). Approximately 75 per cent of this population has sewage services. The flow of water available for irrigation in the ACREs is calculated by considering that in Mendoza 400 litres of drinking water are used per day and that 80 per cent of this returns to sewage, taking into account evapotranspiration in the region and the potential efficacy of irrigation. Table 1 shows the values of available sewage flow and the surface area that could be irrigated with this.

Table 1: Water Available from Treated Sewage in Mendoza Province and Viable Surface Area for Irrigation

ITEM	QUANTITY	UNIT
Population of the province	1,800,000	inhabitants
% served	0.75	75%
Overspill	0.320	m^3/person/day
Reused effluents	432,000	m3/day
Flow rate	5	m3/s
Surface area, summer ACREs	7,142	ha
Surface area, winter ACREs (x3)	21,428	ha

Source: prepared by the author

This theoretical calculation is in line with the presence of ACREs in the territory, shown in Table 2 (Source: prepared by the author).

Table 2: Surface Area of ACREs Irrigated with Treated Sewage in Mendoza

ACRE size	SURFACE
LARGE ACREs	6,300 hectares
SMALL AND MEDIUM ACREs	600 hectares
ACREs to be created or formalised	200 hectares
TOTAL	**7,100 hectares**

4.1 What is an ACRE?

Resolution No. 400/03 of the Honourable Administrative Tribunal of the General Department of Irrigation approves the regulation of Specialised Restricted Cultivation Areas (ACREs) and establishes the parameters for determining the frequency of measurements in Annexes I and II, which form an integral part of this Resolution.

It establishes or defines what is meant by the term ACRE. In Annex I of the aforementioned document it is stated that:

> "**Article 1.2.** States that the purpose of the area referred to as an Area de Cultivos Restringidos Especiales (Specialised Restricted Cultivation Area) (ACRE) is for carrying out the controlled reuse of effluents from a purification facility, which may be used within the framework of sustainable development and which are completely prohibited from being channelled outside of its boundaries or in any way released for unrestricted use. The reuse of wastewater from purified effluents in the aforementioned areas is subject to the general principles relating

to the use of public water such as cost, efficient use, progressive improvement of quality as well as those stated by this regulation."

A number of factors for consideration arise from an analysis of this definition:

- The controlled reuse of effluents from a purification plant is carried out in a defined area. Generally areas are chosen that do not have irrigation licenses, so as to extend the borders of the cultivated area. There is a great deal of industrial activity in Mendoza, a very high percentage of which is in the agrifood industry, (wineries, factories producing fruit and vegetable preserves, sweet factories, must concentrators, etc.) The limit placed on factories for sewage overspill is essentially related to electrical conductivity, which must not exceed 3,000 μS. Virtually no effluents containing heavy metals enter into the sewage system.
- The protection of soil, good farming practices, monitoring of authorised crops and the profitability of production should all be considered within a framework of sustainable development. The monitoring of soil quality has been carried out on several occasions as a basis for certain studies, but has not been carried out systematically by the General Department of Irrigation. In the ACREs there is a network of strategically placed piezometers that allow the phreatic level of groundwater to be assessed and such monitoring to be carried out methodically.
- Reuse water is prohibited from being channelled outside of the ACRE, favouring what is known as 'zero overspill' (*vuelco cero*)[iii]. This aspect is dealt with in more detail in the following section. Wastewater reuse has emerged naturally in Mendoza due to users' interest in replacing groundwater, which is more expensive, with sewage. Furthermore, as ACREs are generally located in areas that do not have irrigation rights, in some cases treated sewage is the only available resource for cultivating crops. Consequently, the state does not need to promote wastewater reuse.
- The principles of public water usage include: cost, efficient use and improving quality.

It should be noted that in the summer demand exceeds supply. New licenses can only be issued in the winter, when there is surplus effluent because crops need significantly less water.

4.2. Winter ACREs

Mendoza's climate is arid and continental, annual temperatures vary considerably and rainfall is low. The summer is hot and humid, and it is the season with the most rainfall with average temperatures of above 25°C and maximum recorded temperatures reaching above 37°C.

The winter is cold and dry, with average temperatures falling below 8°C, minimum temperatures falling below 0°C, occasional night frosts, and low rainfall. Snow and sleet are rare, usually occurring just once per year, although both are light in the highest areas of the city.

The evapotranspiration of crops fluctuates in midsummer between 4.5 and 7 mm/day, depending on factors such as altitude and latitude. In the winter, evapotranspiration drops appreciably by three or four times the summer values.

Resolution No. 500/06 of the HTA establishes what are called 'Winter ACRES' which basically tend to achieve zero spillover. This regulation allows new permits to be issued for wastewater to be used during a period of six months (from April to October every year) and the fee or charge for its use is reduced to 50 per cent of the amount paid for a full year. This type of permit has been issued for more than 1,100 hectares in the Paramillo ACRE and some 200 hectares in the Campo Espejo ACRE.

5. Current Strengths and Weaknesses

The fact that the General Department of Irrigation has for a number of years taken over exclusive responsibility for the management of areas where treated wastewater is reused, it represents an important milestone. Previously, the fragmented and overlapping nature of the regulations, or the inaction (often due to a lack of resources) of various organisations involved tangentially, threatened its efficient management and development. Today, no one disputes that managing ACREs, above all the two large ones (Campo Espejo and Paramillo) with many users and covering large surface areas is a matter for the General Department of Irrigation; nevertheless, it is generally accepted that they could improve their performance of this task.

Another success has been without any doubt the way that ACREs have been managed by Waterways Inspectorates. This feature has brought continuity, transparency and participation to the management process. Nevertheless, the inspectorates must improve their management, complying fully with the obligations set out in Law 6405.

In the case of ACREs small work projects can be carried out by the administration with funds from the inspectorate; another possibility is for medium-sized projects to be carried out by water sub-delegations and later reimbursed by irrigation farmers. In the case of large projects, the province bids on and finances the works with national or international funds that are also reimbursed by users who enjoy a grace period lasting years and longer deadlines.

The quality of the wastewater carried to ACREs through irrigation generally falls within the required parameters for secondary treatment. Nevertheless, due to a lack of investment in some of the facilities of the company that deals with drinking water and sanitation in Mendoza, AySAM SA, and in plants operated by municipalities, wastewater does not reach the required standard of quality (case of Algarrobal, Tupungato). The cost of treating sewage is covered by the users of drinking water, in other words towns and cities. The General Department of Irrigation sells the raw water to AySAM (Agua y Saneamiento Mendoza) or other water and sewage service operators. These companies deliver the treated water for free back to the General Department for Irrigation, which establishes the ACREs and charges the users an irrigation fee. The General Department of Irrigation actually solves a problem for these operators as it has better administrative and technical resources for dealing with the final disposal of the liquids.

6. Conclusion

In Mendoza, a number of favourable coexisting circumstances enable treated wastewater to be reused successfully in agriculture: the climatic conditions, which as has already been mentioned make water a scarce resource that is in high demand for farmers: the existence of a body such as the General Department of Irrigation with more than a hundred years' experience in water management (it should be clarified that in 2012 Resolution No. 293/12[iv] was issued by the Honourable Administrative Tribunal); users' organisations (Waterways Inspectorates) consolidated over time, with the technical and operative capacity to manage reuse areas; the practice of farmers who for decades have used treated sewage and are aware of the associated risks and the care that must be taken when managing it.

Expertise related to its management has been a result of many years of farmers irrigating their land with treated sewage. Added to this are the related official recommendations made by the General Department of Irrigation and other associated organisations. In any event, assemblies have been set up where users can be educated more fully about water-borne diseases and the care that needs to be taken to treat liquids so that acceptable results are achieved that fall within the values required by the existing rules and regulations which, in spite of their shortcomings, provide a defined administrative and legal operational framework. In Mendoza, water is not charged by volume but by the surface area, and the rate at which it is supplied to properties varies according to how much water is available, which is essentially the snowfall in the Andes each year. In all cases, whether the water is clean or treated, the amount charged by the inspectorates corresponds to the service they provide to ensure the water reaches farmers, the cost of the inspector's pay, *tomeros* (which distribute the water in each irrigation channel or gate), operating machinery, maintaining waterways, etc.

Although it must be recognised that significant steps have been taken towards the technical and administrative regulation of ACREs such as the registration of users, managing charges for water use, monitoring authorised crops, and organising irrigation water rotation schedules, we can and should continue to work towards perfecting this unique production system stemming from wastewater reuse that has such value today that it competes with other traditional water sources.

In this context, some actions, if implemented, could improve the integrated systems of treatment:

- Planning and coordination. Today, there is practically no planning or coordination; in Mendoza, a company that deals with drinking water and sanitation is in operation (AySAM SA); other sewage service operators include councils, cooperatives and neighbourhood associations. A regulatory body (E.P.A.S.)[v] intervenes and the General Department of Irrigation manages all water.
- Reformulation of the ACREs Follow-up Committee[vi]
- Review of the current regulations that contain some inconsistencies, overlap and omissions

- Research into the quality of production and health, with the participation of local universities
- Training for farmers
- Construction works in purification facilities and ACREs
- Active participation of other organisations linked to reuse

If the proposed objectives are achieved, agricultural reuse in Mendoza will come to be of significant strategic importance for increasing the efficiency and utilisation of water resources, mitigating the effects of climate change. It will also offer improvements in guaranteeing water given that treated sewage is produced all year round and the flow is practically continuous. In addition to the quantity, with ACREs that are correctly managed and monitored, safe use is guaranteed from a health point of view.

Finally, the Mendoza case study will encourage socioeconomic development given that the reuse of treated sewage enhances the cultivated oasis and generates new job opportunities.

References

General Department of Irrigation (*Departamento General de Irrigación*). 2003. *Resolution Nº 400/03 del Honorable Tribunal Administrativo, Reglamento de Áreas de Cultivos Restringidos Especiales* (in Spanish).

General Department of Irrigation (*Departamento General de Irrigación*). 2006. *Resolution Nº 500/06 del Honorable Tribunal Administrativo, faculta la creación de ACREs de Invierno* (in Spanish).

Magnani, Cesar. 1991. "*Administración de las Aguas en la Provincia de Mendoza. Descentralización y participación de los usuarios como rasgos determinantes de la gestión hídrica de regadío*" (in Spanish). Thesis, University of Mendoza.

Obras Sanitarias Mendoza S.A. 1997. "*Depuración y reuso de efluentes cloacales, Folleto de Divulgación*" (in Spanish). Mendoza.

Pinto ME, Rogero GE, and Andino MM. 2006. "*Ley de Aguas de 1884*" (in Spanish), commented and agreed, 1st ed. Mendoza: Irrigación Edita.

1993. "*Ley de Reordenamiento Institucional. Sector Agua Potable y Cloacas*" (in Spanish). Law 6044/93.

Centro de Ingenieros de Mendoza. 2004. "*Áreas de Cultivos Restringidos Especiales-Ing. León Kotlik*" (in Spanish).

2001. "*Boletín Oficial de la Provincia de Mendoza*" (in Spanish). November 2.

[i] Waterways Inspectorates: non-profit public entities that enjoy self-sufficiency and the full capacity to act in the domains of both public and private law. They select their own officials and draw up their own budgets, in accordance with the provisions of article 187 of the Provincial Constitution. They are fully-fledged organizations set up for all users who hold the right to use public water, which is provided by way of a single waterway or a designated system of waterways. Their powers and functions are governed by Law 6405 and other related laws. The management, use, control, conservation, maintenance and protection of canals, small irrigation channels and drains in the Province, as well as the water that is carried by them, will be the responsibility of the Waterways Inspectorate, subject to the provisions in the sixth section of the single case - the General Department of Irrigation - of the Provincial Constitution.

[ii] UTE: UTEs are a form of business collaboration for undertaking projects, works or services that are too large in scope for just one company.

[iii] Zero overspill (*vuelco cero*): established in an agreement signed between the General Department of Irrigation and Obras Sanitarias Mendoza S.A. in 2000, called the "Convenio Marco para la Implementación de la Política de Vuelco Cero y la Conformación de Áreas de Cultivos Restringidos Especiales (A.C.R.E.)" (The Framework Agreement for the Implementation of the Zero Overspill Policy and the Formation of Specialized Restricted Cultivated Areas (ACREs)), with the aim of reorganizing the reuse of effluents through the implementation of this policy, and so extending the cultivated surface area in the province. The zero overspill policy involves the prohibition of effluent or surplus effluent after irrigation being channelled outside of the boundaries of the ACRE. This condition does not fully apply with the production of residual effluent due to the decrease in water needed for the winter cultivation of crops.

[iv] Resolution No. 293/12 establishes the Department of Water Reuse on the organization chart, putting emphasis on specific functions including identifying feasible areas for reuse, monitoring the physical, chemical and biological parameters of effluents, monitoring of crops, work projects in ACREs, etc.

[v] Provincial Water and Sanitation Organization (*Ente Provincial del Agua y Saneamiento*).

[vi] This committee, made up of representatives from the organizations involved in reuse, monitors the ACREs and proposes actions to improve performance; until now, it has not been correctly implemented..

CASE 15

Varamin Project: A Wastewater Reuse Success Story from Iran (Iran)

Mohammad Javad Monem [1]

Abstract

Limited water resources, increasing water requirements and competition over water resource consumption in different sectors have become major challenges. Much has been done to find new sources of water. Population growth and urbanisation have produced more wastewater, which could be considered as a new source of water. This source of water is important for agricultural production, which is the greatest water-consuming sector. In the past, wastewater was used mainly to increase the fertility of the land. Nowadays the main motivation for wastewater reuse is water shortages. Wastewater reuse in agriculture involves several considerations in terms of the quantity and quality of the wastewater. The impact of wastewater reuse on health, the environment, soil, crop and other surface and groundwater resources should be carefully investigated.

Specific monitoring activities should be taken into account, and high standards for wastewater reuse should be implemented. The economic, social and agricultural evaluations are important aspects which are central to the investigations. Iran is a water-scarce country, urbanisation is increasing and its population is growing; therefore, the

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country is planning for more wastewater reuse in agriculture. The Varmin irrigation project is a successful example of such a plan. The initial wastewater reuse system was established in 1988. Due to the deteriorating conditions of water shortage, a development plan for increasing the capacity of wastewater reuse is underway that will be completed with the collaboration of the private sector. Presently 120 million cubic meters of wastewater are used in the Varamin irrigation network, which will be increased to up to 280 million cubic meters after the completion of the development plan.

Keywords: wastewater, irrigation, health risks, water use efficiency, private sector

1. Background

Population growth, improving living standards and welfare, and climate change have led to their being less water per person worldwide. Iran is located in an arid region and the water shortage crisis threatens the area more seriously and has passed the water stress limit. Among other sectors, the agricultural sector is the top water consumer. About 70% of accessible world freshwater is used in agricultural activities, while this figure is 92% in Iran.

More fresh water can be prepared by improving water use efficiency, increasing storage capacities, applying modern water harvesting methods, and water and wastewater treatment.

Even though the amount of water and wastewater treated compared with total water requirements in agriculture is low, it could still be a substitute for high quality water, and result in the allocation of high quality water for more important purposes such as drinking water.

Urbanisation is increasing worldwide and more wastewater is produced each day. Due to a low awareness of the benefits of wastewater treatment, wastewater is not considered an important source of water in water resource planning. Limited water resources, the increased volume of wastewater production, and the improvement of general awareness regarding the issues, has attracted the attention of water stakeholders in order for wastewater to be used wisely. In developed countries sewage treatment reuse is carried out in line with environmental regulations. The centrepiece of this legislation is to protect human health, preserve the environment, and prevent soil and water pollution. While in developing countries, in addition to treated wastewater, raw sewage is also used for agricultural production. Developing countries lack the proper strategy and plans as well as specific instructions on the use of wastewater, which as a consequence increases the health and environmental risks, as well as water and soil pollution.

2. Effects of Using Wastewater for Irrigation

Many studies have shown that the consistent use of urban wastewater in addition to expanding vegetation, on the one hand, prevents environmental pollution and, on the other hand, reduces the costs of using fertilisers due to the high levels of nutrients. Researchers suggest that appropriate levels of wastewater reuse improve the physical condition of soil while providing a considerable amount of necessary fertiliser, but too much wastewater is harmful for crops and decreases the performance and quality of the crops.

The proper utilisation of municipal sewage reduces pollution in surface water and preserves water resources. The effluents are available near urban centres and provide the potential to increase agricultural production around cities, which are a promising market for farmers.

The impacts of wastewater reuse for agriculture on health, soil, and crops should be carefully taken in to account. The accumulation of high toxic substances in the soil and in plants and animals and their entry into the human food chain are important issues for human health and need to be considered. When reusing sewage, in addition to chemicals, the transmission of infectious agents such as bacteria, parasites, (protozoa and worms) and viruses must also be considered.

The impact of wastewater on soil quality in arid areas, with high temperature, low humidity and high evaporation, is of particular importance. The physical and mechanical properties of soil, such as strength, porosity, structure and hydraulic conductivity, are sensitive to ion exchange. A major concern in the use of treated wastewater to irrigate crops is the presence of dangerous compounds with high concentrations, such as many rare and sustainable materials, organic and complex configurations, and micro pollutants in the irrigation water.

The reuse of wastewater can cause the following positive and negative effects: reduce the pressure on water resources, reducing the cost of agricultural water, reducing costs of fertilisers, increasing agricultural production, reducing environmental pollution, and access to cheaper sources of water for drinking and sanitation.

The environmental side effects of reusing wastewater include: imbalance in wastewater supply and agricultural demand which will be harmful to the environment by releasing unused wastewater in nature, increased risk of some harmful and toxic substances, and social and psychological adverse effects of wastewater reuse for agricultural crop production.

3. Monitoring

The monitoring of a wide range of water quality parameters is essential for the safe use of wastewater in agriculture. The annual monitoring of chemical and biological parameters, both before and after irrigation, is essential. Changes may be associated with sources of wastewater, treatment processes, population variations, and changes in industrial capacities; therefore, monitoring methods should be adjusted accordingly. Monitoring should include all processes and installations including: treatment of plant installations, transmission, and distribution systems, surface and ground waters, soil, plants, and the health status of workers, farmers and the public in accordance with acceptable standards in their entirety.

4. Introduction to the Varamin Irrigation Project

Feasibility studies for the Varamin Irrigation Project for 50,000 hectares of land were carried out in 1971 by the Food and Agriculture Organization (FAO). Supplementary studies were conducted by Mahab Ghods Consulting Engineers Co. from 1971 to 1973. Executive work started in 1975 and ended in 1988 and the networks came into operation after that. Figure 1 shows the location of the project (Tehran Sewerage Company 2012).

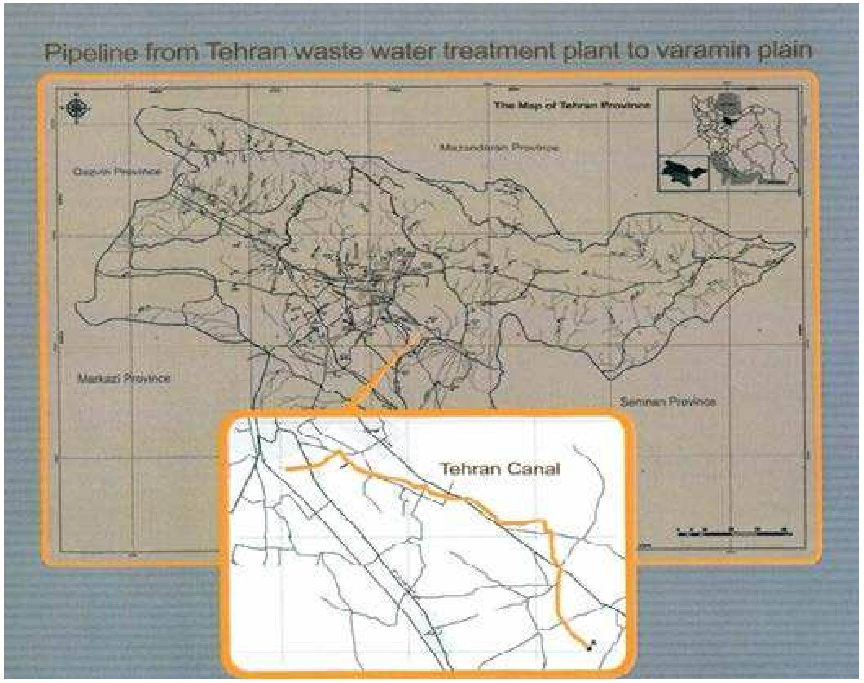

Figure 1: Location of the Varamin plain and Tehran Canal (Tehran Regional Water Company 2012)

The Varamin network consists of 82 km of main and secondary canals and 384 km of distributary canals (Figure 2). The total annual water requirement of the Varamin Irrigation network is about 600 million cubic meters, which was supposed to be supplied by the Lar Dam on the Jajroo driver and groundwater. Due to the expansion of the capital city and the rise in domestic water requirements, a portion of the Lar reservoir was allocated to Tehran, which was supposed to be substituted by treated wastewater from the Southern Tehran treatment plant.

The agricultural areas south of Tehran are located near the largest consumer market for crop production. This helps farmers to produce more profitable crops (vegetables). Varamin plain is one of the major centres of vegetable production.

A significant level of land for growing vegetables is directly irrigated by sewage. Watering vegetables is mainly done by flooding, and water directly contacts the plants and in some cases the entire plant is submerged.

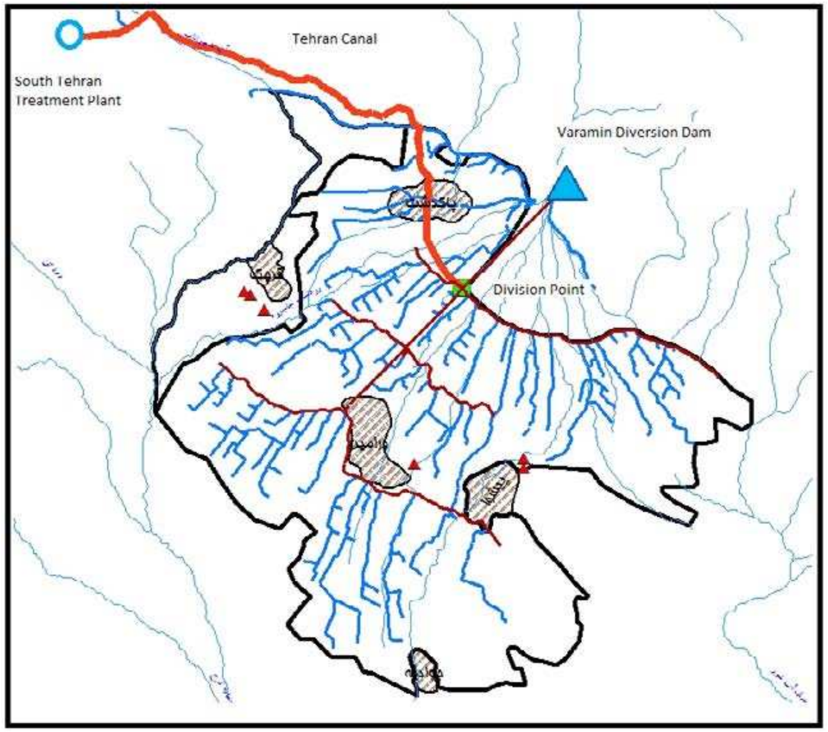

Figure 2: South Tehran Treatment plant, Tehran Canal, and Varamin Irrigation Network (Yekom Consulting Engineering Company 2007)

Due to the presence of chemical elements and various microbial agents in the wastewater, the entry of harmful elements into the tissues of plants and microbes transmitted by the product is very likely. Since in many cases vegetables are washed only with water, are not disinfected, and are eaten raw, the potential risks to public health are high.

One of the most important design components of the Varamin Irrigation network is the Tehran Canal with the length of 36 km, and a design capacity of 8 cubic meters per second see Figure 3 (Yekom Consulting Engineering Company 2007).This canal was intended to supply 200 million cubic meters of treated wastewater from the Tehran Southern treatment plant per year, 50 million cubic meters for groundwater artificial recharge, and 150 million cubic meters for agricultural consumptions. Therefore about 25 to 30 percent of water requirements for the project were supposed to have been provided through wastewater recycling.

Figure 3: Tehran Canal after the South Tehran Treatment Plant (Yekom Consulting Engineering Company 2007)

Due to the lack of a wastewater collection system in Tehran and a delay in completing the South Treatment Plant, the design objective was not achieved. Therefore the consumption of ground water increased significantly and the groundwater table declined more than the allowable limit on the Varamin plain and has reached the critical limit. According to the latest studies the average annual groundwater level decline on the Varamin plain, with an area of 1,112 ha., has reached 1.47 m, and annual groundwater reservoir depletion is 49 million cubic meters. The 10 km long Afsarieh canal with a capacity of 4 CMS was constructed to convey the eastern sewage of Tehran to the Varamin plain. Nearly 4 km of the Tehran Canal passes through residential areas. For environmental, social, health, and safety considerations this portion of the canal is built as a concrete box. Figure 4 shows the division point of the Varamin irrigation network.

Figure 4: Varamin Network Division Point (Tehran Sewerage Company 2012)

After 25 years of constructing the Tehran canal, the rural area around the canal has expanded, which has imposed many limitations and alterations on the canal (Figure 5). Although the initial capacity of the Tehran canal was 8 CMS, due to alterations and the lack of appropriate maintenance, the present capacity is much less than that.

Figure 5: Tehran Canal Passing a Residential Area (Tehran Sewerage Company 2012)

5. Development Plan

The working capacity of the Tehran Canal during recent years was 4 CMS, conveying about 120 million cubic meters of effluent from the treatment plant to the Varamin plain. With the completion of 6 units of the southern treatment plant since 2010, and the completion of 8 units in the near future, the annual effluent of the treatment plant will reach up to 280 million cubic meters at a maximum rate of 13 CMS. In order to increase the capacity for using effluent from the treatment plant, a comprehensive development plan is put forward and thorough studies on the agricultural, social, environmental, technical and economic aspects have been carried out.

The main component of the development plan is the construction of a pipeline to convey treated wastewater from the Tehran South Water Treatment Plant to the Varamin plain. This pipeline, laid next to the Tehran Canal, is connected to the south wastewater treatment plant's effluent point in Shahre Rey and continues all the way down to Varamin. The total length of the pipe line is 36 km.

By implementing this project, an extra 9 CMS of wastewater will be conveyed to the plains of Varamin, Pakdasht and Shahre Rey. The plant's maximum effluent rate is 13 CMS, 4 CMS of which is currently conveyed to the Varamin plain by the existing Tehran Canal. This system conveys an annual amount of 280 million cubic meters of wastewater from the south treatment plant to those plains, which is used for agricultural irrigation (230 million cubic meters) and groundwater artificial recharge (50 million cubic meters).The system has an intake at the exit point of the wastewater treatment plant and a GRP pipeline (3 meters in diameter by 36 km in length), which will be laid adjacent to the present Tehran Canal. The depth of the ditch will be between 5 to 7 meters. The round-the-clock regulation of wastewater fluctuations will be damped by three pools at the end of the line, with a total capacity of 120 thousand cubic meters.

6. Mechanisms of Financing the Project

The estimated cost of the project is 1,600 billion Iranian Rials. The funding of the project will be undertaken by a private sector financer.

The Build-Operate-Transfer BOT agreement and guaranteed purchase of effluent from the private sector over a period of 15 years was on the agenda of the Tehran Regional Water Company. A public call for tenders in newspapers was announced, and 21 private investor pre-qualification tender documents were received from the companies.

It was decided to attract private sector initiatives by providing ownership of up to 30 million cubic meters of wastewater per year to the investor. Also, the government proposed pre-buying effluent for a transitional period of one year from the investor. In addition the private sector requires guarantees for the repayment of the investment by the Central Bank of Iran, and assurance for the water price.

7. Summary/Conclusion

Increasing water demand and high competition over water use in different sectors have made it necessary to search for new water resources. Population growth and increased urbanisation have led to more wastewater production. Wastewater is considered as a new water resource especially for agricultural use. Several important considerations regarding environment, health, social, and economic issues should be taken into account for the wise use of wastewater in agriculture. High standards for the monitoring, design, execution, and operation of the whole process should be developed and implemented. The development plan for wastewater reuse in the Varamin irrigation network in Iran is a good example of such a project. Using the capacity of the private sector for investment in the project, along with providing required guarantees and incentives, was a successful approach for the Varamin irrigation network.

References

California State Water Resources Control Board, 2990, Department of Land, Air and Water Resources. 1985. *Irrigation with Reclaimed Municipal Wastewater: A Guidance Manual*. Edited by G. Stuart Pettygrove and Takashi Asano. Davis, California: Lewis Publishers, Inc.

Food and Agriculture Organization of the United Nations (FAO). 1992. "Wastewater treatment and use in agriculture." Publication No. 24. Rome: FAO.

Planning and Guidance Control Deputy President. 2009. "Guideline for studies of plans for urban and rural treated wastewater reuse" (in Persian). Publication No. 434.

Tehran Regional Water Company. 2012. "Pipeline from Tehran wastewater treatment plant to Varamin plain." Project brochure.

Tehran Sewerage Company. 2012. "Description of Tehran metropolitan sewerage Project."

World Health Organization of the United Nations (WHO). 1989. "Health guidelines for the use of wastewater in agriculture and aquaculture." Report of a WHO scientific group, *Technical Report Series 77*. Geneva, Switzerland.

Yekom Consulting Engineering Company. 2007. "Development plan of saline, brackish, and unusual water use in water basins of the country" (in Persian). Report No. 6, *Appropriate policies and strategies for saline, brackish, and unusual water use*.

CASE 16

Council for Certification of Irrigation with Treated Water in Mexico (Mexico)

Carlos Antonio Paillés Bouchez [1]

Abstract

The development of Wastewater Treatment Plants for Agricultural Irrigation in Mexico and Latin America has taken a long road, starting in Belem, Brazil, in 1999. Implementing more than 30 of them as Pilot Projects in the states of Oaxaca, Puebla and Hidalgo, with demonstrative irrigation parcels has not been enough to create replications by the local water and agricultural organizations. The Culture of Water in our countries does not include the importance of the treatment of wastewater. By 1950 less than 10% of wastewater was treated. By 2000 this percentage had not reached 25%. The concept of the reuse of such water is extremely limited, including Engineering, Agriculture and Economic Schools. In communities where the pilot projects were implemented, less than 1% of the people, including teachers and government officers, knew about the Safe Use of Wastewater in Agriculture (SUWA). At the same time, thousands of hectares were irrigated with untreated wastewater with some kind of participation by national and local governments. Prohibition by itself has never worked in the world. In the last 15 years, the Certification of Competences in México has been accepted by workers, farmers, corporations, labour

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unions and government agencies as a good instrument to qualify persons in charge of specific activities. The establishment of the Council for the Certification of Irrigation with Treated Water in Mexico intends to promote the day-to-day, person-to-person, acceptance of SUWA objectives.

Keywords: capacity building, agricultural irrigation, environmental health, food safety

1. Introduction

Mexico has the largest agricultural surface irrigated with untreated wastewater in the world (90,000 hectares in one single irrigation system) (CONAGUA 2015).

The construction in 1900 of a 32 km tunnel, 6 m in diameter, to take rainwater and the wastewater from Mexico City was a civil engineering triumph at the time, without any kind of sanitary/health/agricultural/environmental prevention within the following 100 years, especially in the Tula River Basin, where the water was delivered. Two consecutive droughts in 1976-77 gave room for temporary authorization by the Mexican Government to deviate this water to the irrigation system of the Mezquital Valley. This temporary deal has been extended to the present.

In August 1999, two United Nations (UN) agencies, the United Nations Environmental Programme (UNEP) and the Economic Commission for Latin American (ECLA), with the close participation of the World Health Organization (WHO), the Food and Agriculture Organization (FAO), the World Bank and the Inter-American Development Bank (IADB), invited the water organizations of the continent to present alternatives for water treatment based around the Safe Use of Wastewater in Agriculture (SUWA) options in rural towns, during a workshop held at Belem, Brazil. The Mexican proposal, presented by one of the Environmental Trust Funds, was endorsed by the IADB in 2000 and included in the brand new Program for the Sustainability of the Water and Sanitation Systems (PROSSAPyS) in rural communities (CONAGUA 2001).

The implementation of 20 pilot projects in the states of Oaxaca and Puebla demonstrated the capabilities and limitations of this kind of solution. Six Wastewater Treatment Plants (WWTPs) in the rural towns of Ixtlán and Capulalpam, in the Sierra Norte of Oaxaca, which have been operated without interruption by the same farmers in these the towns since 2003, are real examples of these options. The political riots of 2006-2007 in Oaxaca interrupted this positive trend. In 2008 the Federal Government (CONAGUA) took the decision to build a Macro WWTP in Atotonilco to treat wastewater from the Valley of Mexico (35,000 lps, the largest in the world). In the same year CONAGUA and the State of Hidalgo signed a Framework Agreement with the Environmental Infrastructure Trust Fund for the Valleys of Hidalgo to establish ten or more WWTP pilot projects for SUWA purposes, to prepare the local communities for this new option of treated water for agriculture.

Within the many operational points to be developed in these pilot projects, one important asset required special attention: the *capacity construction* and the *competences certification* for the correct and appropriate management of treated wastewater for agricultural irrigation. It took 2 years to develop and complete the process for the constitution of the Comite de Gestión de Competencias para Riegos Agrícolas Tecnificados con Aguas Residuales Tratadas (Council for the Certification of Irrigation with Treated Water in Mexico), including the publication in the Official Newspaper (Diario Oficial de la Federación 2015). This case is an attempt to share our points of view and the experience we gathered during the establishment of the process.

2. Significant historical events

1800s: US population grew from 5 million to 75 million. Primary Development: Collection Systems. Primary Purpose: Disease Prevention. *Treatment was mostly dilution into receiving waters.*

1887: First biological treatment, an intermittent sand filter, was installed in Medford, Massachusetts.

1899: First federal regulation of Sewage, Rivers and Harbours Appropriations ("Refuse Act") prohibiting discharge of solids to navigational waters without permit from US Army Corps of Engineers.

1900s (early): 1 million people served by 60 sewage treatment plants for removal of settling and floating solids. Trend: population growth and sewer construction

1900–1930s: Sewered population increased at same rate as total population. Trend: development of secondary (biological) treatment.

1909: First Imhoff tank (solids settling) (Cooper 2003).

1914: First liquid chlorination process for effluent disinfection.

1916: First activated sludge plant, San Marcos, Texas.

1920–1940s: Wastewater treatment linked with importance of dissolved oxygen to aquatic life, aesthetic properties of surface waters (odour, colour, solids), measurement of organic matter in sewage as biological oxygen demand (BOD). *Increased wastewater treatment meant increased residuals (sludge). Elimination of Nutrients.*

1960: Milestone. 50% of US population had access to some form of wastewater treatment.

1960–present: Trend: Treatment process advances to improve receiving water quality.
Nutrient (nitrogen and phosphorus) removal. New process configurations: high-rate activated sludge processes, high-purity oxygen, sequencing batch reactors, high-rate trickling filters and hybrid trickling filter-activated sludge processes, membrane bioreactors. Trend: Regulation.

1972–present: Federal Water Pollution Control Act Amendments (PL 92-500, known as the Clean Water Act) et seq. until 2002. CWA summary, Water Quality Standards for receiving water (based on designated uses and related human health and aquatic life criteria). Antidegradation policy with environmental monitoring. If WQS not met: plan (strategies and controls) to improve impaired water using Total Maximum Daily Load (TMDL) approach. Control of toxins, industrial pre-treatment sludge. Biosolids disposal. Section 404 (Wetlands protection). State Revolving Funds.

Emerging Trends: *Wastewater Reuse*, Non-Potable, Separate Distribution Indirect Potable, Direct Potable Local Regulation. Energy Recovery (Biofuels, Co-Generation, Fertiliser), Conservation of Energy (Aeration, Pumping, Mechanical Solids Processing, Heating, Embedded Materials).

3. Patterns for WWTP for Agricultural Irrigation as per WHO SUWA Guidelines

In the historical references the predominance of WWTPs aimed at returning treated water to rivers, lakes and seas was outlined. The Activated Sludge model was repeated several times, probably in up to two-thirds of cases, throughout the twentieth century, and the first 15 years of the twenty-first century. The most important part of this model *is the elimination of nutrients* (Sanitation District of Los Angeles County 2011). With this elimination, the most important value of the wastewater is disregarded. More importantly, trying to use treated water in agricultural irrigation without nutrients and plenty of chemicals, such as *chlorum*, is complicated, useless and sometimes counterproductive.

The current SUWA guidelines issued by the WHO (2006) are based on the six points shown in Figure 1:

- Acknowledgement of the agricultural nutrition values of many of the components of domestic wastewater.
- Complete knowledge of the many contaminants of the wastewater and existing risks in their use.
- Complete knowledge of the agricultural irrigation process, from the initial sequences of the wastewater to the absorption processes within the different crops, passing through the most important filter in the world, the soil, including all irrigation technologies.
- Simultaneous consideration of different health hazards, (human, vegetal, animal, environmental, etc.).
- Adequate use of the risk management process.
- Historical, geographical and social conditions of wastewater use (or management).

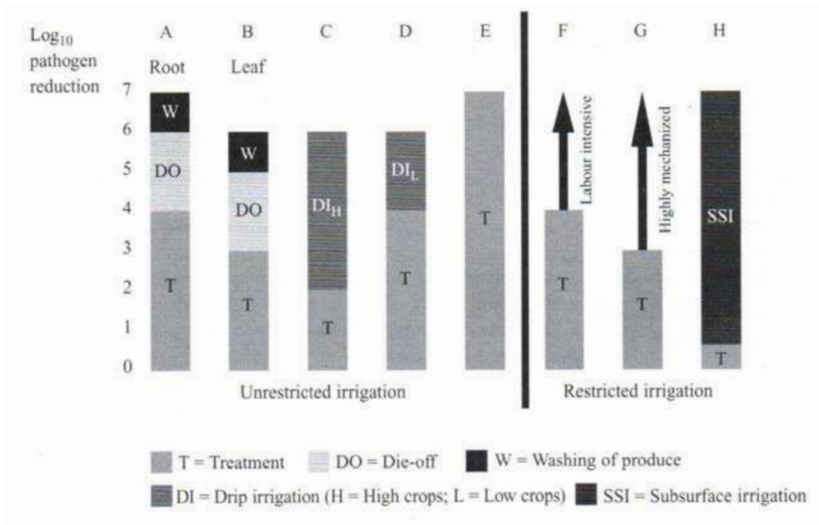

Figure 1: Examples of options for the reduction of viral, bacterial and protozoan pathogens by different combinations of health protection measures that achieve the health-based target of ≤ 10^{-6} DALYs per person per year

In 1999-2000, with these considerations in mind, the Environmental Infrastructure Trust Fund made a full review of the various alternatives for the treatment of wastewater in 12 different countries, with the emphasis on agricultural reuse. Checking the research papers of the WHO SUWA guidelines, special attention was paid to the differentiation of crops in relation to irrigation and systemic processes. The operational substance of the guidelines is briefly explained in the next few paragraphs.

There are three different kinds of crops, as per SUWA patterns.

A. Trees and large bushes, which requires basic *control devices* for the correct use of treated wastewater and adequate management.
B. Large, medium and small stem crops, (corn, quinoa, beans, tomatoes, broccoli, etc.), which require specific biological treatment processes for the wastewater to reach a 75-80% level, (secondary treatment), drip irrigation to avoid human contact with treated water, and adequate crop management.

They represent roughly 70% of the world's edible crops, as illustrated in Figures 2 and 3:

Figure 2: WWTP with quinoa crop (Acoculco, Hgo.)

Figure 3: WWTP with tomato crop (Tecamachalco, Pue.)

C. Leaf and root vegetables, on which treated water makes contact with the edible product (lettuce, spinach, carrots, beets, etc.), requiring qualified tertiary treatment, in addition to the secondary treatment, to reach a 97-99% level.

They represent roughly 20% of the world's edible crops, as illustrated in Figures 4 and 5:

Figure 4: Spinach crop with protective soil cover

Figure 5: Vegetable crops ready for the local market

Specific design patterns were obtained and patented for the B and C processes, (secondary & tertiary) and implemented in different WWTPs (90% type B and 10% type C).

4. Wastewater Treatment Plants for SUWA Purposes Under the State/Federal/Municipal Framework, 2008-2013

With the signature of a Framework Agreement between the Hidalgo State Water and Sanitation Commission and the Environmental Infrastructure Trust Fund (FIAVHI), with the testimonial participation of CONAGUA, for the implementation of 10 initial WWTPs for agricultural reuse, an important prospect was developed for the implementation and evaluation of the SUWA's potential impact in the largest group of untreated irrigation districts in the world: the Mezquital Valley.

The fourth of those ten WWTPs, San José Acoculco, within the Atotonilco de Tula Municipality, was developed together with an agricultural farmers' organisation, Ejido Progreso, including secondary and tertiary processes, directly receiving wastewater from the Valley of Mexico, 900 meters from the largest WWTP in the world, Atotonilco de Tula, to provide CONAGUA, the State of Hidalgo, the different municipalities surrounding the valley, and, very importantly, the large number of agricultural users of untreated wastewater (more than 90,000), with management, maintenance, production yields, sanitation controls, and the many different parameters of a real WWTP under SUWA guidelines, to be considered in the Macro WWTP being implemented.

The San José Acoculco WWTP, a pilot project, was completed in 2011 to treat 500,000 litres per day (5 lps) to irrigate 20 ha, and has been in daily operation since then (4 years), as shown in Figure 6, with the following results:

Figure 6: WWTP at San José Acoculco, Hgo.

4.1. Treatment Levels

4.1.1. Secondary Treatment

Five independent reactors, designed to retain the different bacterial colonies at their maximum, provide treated wastewater which meets the Log10 pathogen reduction recommended by WHO-SUWA, (Examples of options for the reduction of viral, bacterial and protozoan pathogens by different combinations of health protection measures that achieve the health-based target of ≤ 10^{-6} DALYs per person per year). The three types of logarithmic reduction in the WHO guidelines combine treatment and drip irrigation in different percentages corresponding to low-stem, medium-stem and high-stem crops.

Figure 7 shows the levels of reduction reached in different WWTPs in a measurement process conducted by specialists from the Oriental Centre for Ecology and Biodiversity (BIOECO), under an agreement with the Environmental Agency of the Ministry of Science, Technology and Environment of the Republic of Cuba.

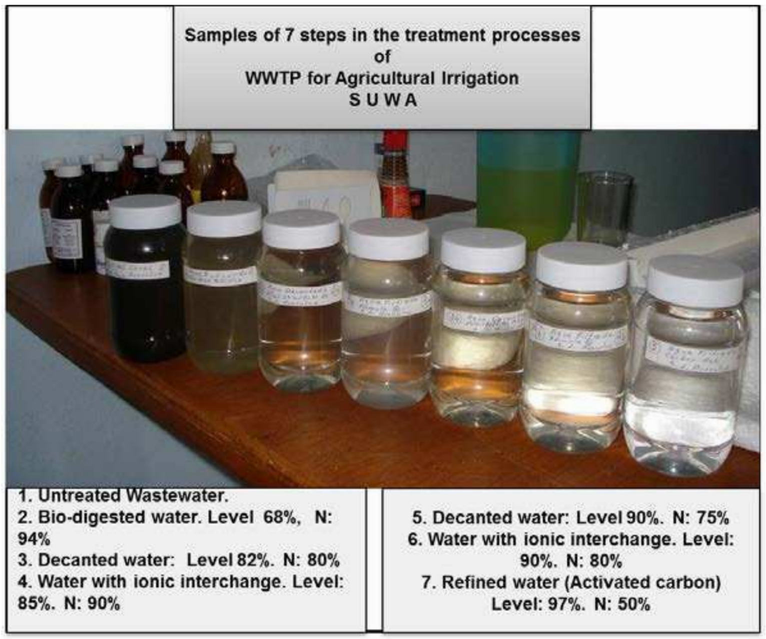

Figure 7: Samples of 7 steps in the treatment processes of WWTPs for Agricultural Irrigation, SUWA

4.1.2. Tertiary Treatment

A combination of coagulation and flocculation processes generate floccules of organic matter, mainly nutrients, which are sent to 20 decantation canals, each with the correct valve, for demonstrative and operative controls (5 to 100%) of their elimination. Once the percentage level is decided, the water enters an artificial precipitation chamber to receive additional oxygenation before flowing into 16 aluminium silicate filters which produce an ionic interchange to increase the treatment level substantially.

There are three options to reach level 8 of the logarithmic pathogen reduction (not required by WHO-SUWA, but to ensure that level 7 has been reached): activated carbon, ozone filter system, and glass fibre spherical multivalve system.

4.2. Agricultural Output

Crop yields: crops irrigated with treated wastewater have three important outputs under WHO Guidelines:

4.2.1. An Increase in Productivity

The measured content of natural fertilisers in correctly treated wastewater, together with the rational use and management of this kind of water, has shown increments in productivity at the following levels:

Crops	Ton/ha. average	SUWA	Crops/year average	SUWA
Beans	2.0	3.2	1	2
Tomato	8.9	24.5	5 cuts	10 cuts
Fava	2.8	4.6	1	2
Peas	1.8	3.0	1	2
Quinoa	1.3	6.2	1	3

4.2.2. An Important Rise in Produce Quality and Prices

As required in WHO Guidelines, the washing of produce and the Good Agricultural Practices inherent to this kind of management increase the quality and price of the crops.

FIAVHI calls this process the ADD A ZERO GAME. It means that the farmer is going to have 10 times the money he/she used to get at the end of the year, but he/she needs to commit 10 times the attention he/she used to give to the crops.

4.2.3. Valuable Savings in the Amount of Water Used

Although this concept is due mainly to the drip irrigation system, it is valid to consider it within the "package" of SUWA proposals. There are savings in the amount of water of 50 to 80% compared with traditional flood irrigation. In FIAVHI projects, a rule of thumb means irrigating three times the amount of the surface that was under flood irrigation.

4.3. Health and Sanitation Controls

Working in the largest area in the world for the continuous irrigation of untreated wastewater, the introduction of treated wastewater has demonstrated controls in the following concepts:

4.3.1. Human Health

Food safety encompasses activities to guarantee maximum possible safety in the process from food production to consumption ("farm to fork") (European Food Information Council 2014). Foodborne diseases include a wide spectrum of illnesses that represent a growing public health problem worldwide. A food safety programme requires healthy and nutritional food ingredients, free of biological, chemical and physical hazards. All regulations should cover these concepts.

The most common foodborne problems are (WHO 2000):

- The spreading of microbiological risks (including bacteria such as Salmonella or Escherichia coli). However, food intoxication may happen due to the consumption of contaminated food containing previously produced toxins. It is not necessary to ingest living microorganisms.
- The presence of chemical contamination in food. It is very important to fulfil regulations on this matter regarding industrial and agricultural activities.
- The evaluation of new food technologies. It is necessary to support surveillance systems to cover food safety all along the global food chain.

The picture of one regular user of untreated water (Figure 8) in the Mezquital Valley in Mexico is worth 10,000 words. It is important to spread SUWA practices (Figure 9). Although the treated wastewater has reduced health risks to the greatest possible extent, the same WHO guidelines stipulate no contact at all between farmers/irrigators and the water.

Figure 8: Flood irrigation with untreated wastewater in the Mezquital Valley

Figure 9: Baby squash export crop grown with SUWA practices. Tepetitlan, Hgo.

4.3.2. Animal Health

The large surfaces irrigated with untreated wastewater and the canals that deliver this water to the fields have produced a kind of subculture that includes animals drinking the liquid.

This ingestion results in weakness and illness among herds. Unfortunately, most of the animals are grown for meat, transferring their contamination to human consumers, with very unhealthy consequences.

4.3.3. Environmental Health

The toll on environmental health should be very high without the existence of the extraordinary filter system in the soil. As an example, many families of worms, whose eggs are found in untreated wastewater, find a good location for living in the soil where they were delivered, without interfering with environmental health (Siebe 1998).

But the presence of huge amounts of untreated wastewater for 2-3 weeks in the "irrigated fields" and their canals generate an intensive spread of contaminants (liquids, aerials, solids, etc.), which results in a low-quality environment.

4.4. Maintenance and Management of the WWTP

Two of the basic requirements established as part of the process for the proper design of WWTPs for agricultural reuse were:

4.4.1. A Simplified and Easy Way to Maintain the WWTP

The sophistication of most of the traditional WWTPs (mainly activated sludge) requires very qualified attention for maintenance, giving way to interruptions in operation if the required technicians are not present. The secondary treatment of FIAVHI WWTPs can be maintained in 30 minutes a day by one person with 2 weeks of training. Tertiary treatment requires a combined operational and maintenance cycle performed by one person with 8 weeks of training.

4.4.2. A Sustainable Management of the WWTP

For the sustainable management of the WWTP using an appropriate and economy-wise operation, two important human components are present in the WWTP for agricultural irrigation:

A: users of the sanitation process.
B: users of agricultural irrigation.

Both sides have a specific interest in the correct operation of the WWTP. In small towns (the programme is aimed at towns with fewer than 2,500 inhabitants), most of the A people are B people and all the B people are A people. In all successfully developed cases, the WWTP Committee is made up of B people. Their interest in obtaining better irrigation water is the basis for good management. The value of SUWA/WHO treated water, converted into agricultural produce, necessarily gives a return value to cover the WWTP's operational expenses. The Inter-American Development Bank, one of the financial sponsors of this programme, has strongly endorsed this operational option.

4.5. Capacity Building and Agricultural Irrigation Extension

Every single human-driven activity in history has required the transfer of skills from person to person, social entity to social entity, etc. Nevertheless, agricultural actors and rural communities, who are responsible for the actual agricultural production, have been reluctant to change. The agricultural extension system has been one of the most valuable tools in introducing and sustaining the correct use of treated wastewater in agriculture.

4.5.1. Acceptance from Potential Users

Looking at the benefits described above, it should be very easy to expect that potential users, i.e. agricultural actors, would accept this irrigation option.

In every single WWTP implemented by FIAVHI, there have been small- or medium-sized groups interested in the advantages described and accepting of the limitations and duties required for the adequate success of this kind of irrigation.

4.5.2. Controls and Local Regulations

There are no specific regulations in Mexico regarding the use of wastewater in agriculture, either treated or untreated. In close cooperation with universities, FIAVHI has prepared initial proposals to reach the first level of federal regulations regarding SUWA matters. For good or for bad, all water regulations in Mexico are federal. The states have some responsibilities derived from delegations made by the federal government. Municipalities have some legal capacities dealing with distribution and the operation of municipal water and sanitation systems.

In this search of the means and ways to achieve rules and controls, the Technological University of Tula - Tepeji (UTTT), being a certified entity for competences, with different programmes for capacity building, invited FIAVHI to develop the Certification of Competencies in the Safe Use of Treated Wastewater in Irrigation.

The main thought of both the UTTT and FIAVHI was to be engaged in a new way in recognising the capacities and competencies of those involved in wastewater irrigation, from local farmers to government officers, passing through technicians, engineers, salesmen, teachers, etc., to establish specific rules within the federal government's sphere of influence.

5. The Certification of Competencies in the Safe Use of Treated Wastewater in Irrigation (CMC)

What is CMC?

The Competencies Management Council is a group of individuals, companies or organisations representing productive, social or governmental sectors, which due to the number of workers and participation in the labour market as well as nationwide recognition in the sector, acts as the responsible body for promoting the concept of competency management in organisations representing each sector.

CMC Objectives:

- Promote the development and implementation of the National Competencies System in its sector.
- Define the human capital agenda for competitiveness in its sector.
- Develop and update Competency Standards (CS), Competency Assessment Instruments and consequence mechanisms that encourage the certification of workers in the sector.
- Monitor and promote excellence in the implementation of solutions in its Evaluation and Certification sector (CONOCER 2008).

The Operating Model of the Competencies Management Council (CMC) is illustrated in Figure 10 below.

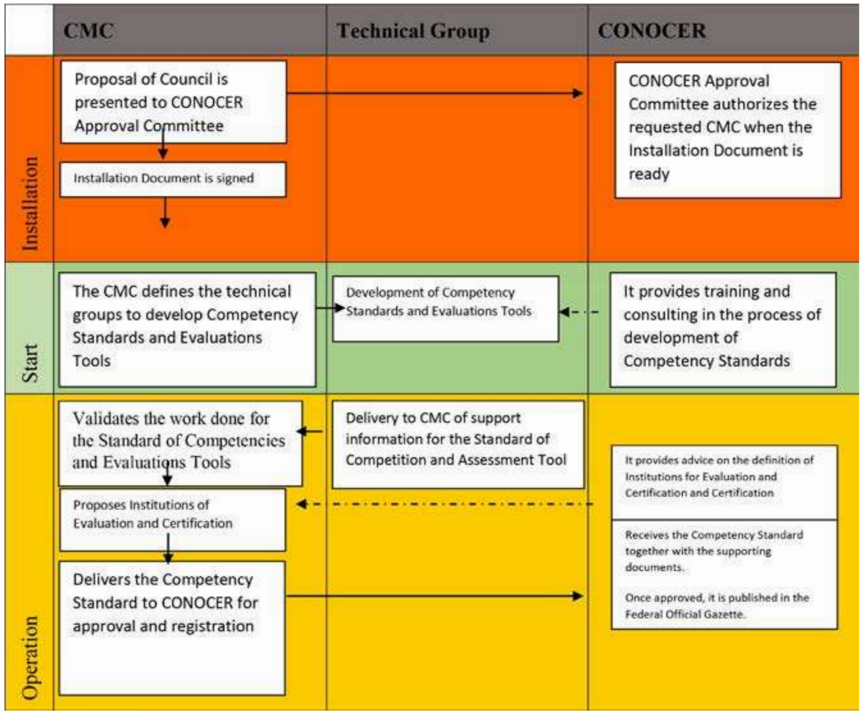

Figure 10: Operating Model of the CMC

Competencies Management Councils can be integrated at the request of associations, chambers and confederations of enterprises, companies, trade unions, social institutions and organisations at various levels of government interested in joining the National System of Competencies and certifying the capacities of their workers, with the possibility of one or more committees being valid for each sector of economic, social or government activity. Councils must meet three criteria for integration:

- Scope
- Representation
- High-level dialogue

Participating institutions are as follows:
- UTTT (Technological University of Tula Tepeji)
- FIAVHI (Environmental Infrastructure Trust Fund for the Valleys of Hidalgo)

- CONAGUA (Management of Irrigation Districts. Branch of Hydro-Agricultural Infrastructure)
- SAGARPA (Directorate of Capacities Development and Rural Extensionism)
- UNAM (Department of Soil Science. Institute of Geology)
- Ejido Progreso Atotonilco de Tula

What these organisations are looking for is specialisation in the safe use of treated wastewater in agriculture.

Currently seven other institutions are offering Certification Competency Standards (EC).

- Assessment and Certification Entity of the Autonomous University of Chapingo (Texcoco, State of Mexico)
- Assessment and Certification Entity of the Universidad Autonoma Agraria Antonio Narro (Saltillo, Coahuila)
- Agricultural Technology Center No. 109 (CBTA 109 Capulalpam Mendez, Oaxaca)
- Technological University of Tecamachalco (Puebla)
- Technological University Francisco I. Madero (Tepatepec, Hidalgo)
- Assessment and Certification Entity of the Technological University of Valle del Mezquital (Ixmiquilpan, Hidalgo)
- Assessment and Certification Entity of the Technological University of Tula-Tepeji (Tula de Allende, Hidalgo)

The estimated population that performs functions on issues related to agricultural land irrigated with treated wastewater is 90,000 persons, which are likely to certify approximately 4,470 people over a period of 10 years. There are 90,000 registered water users in organisations that have agreements with rights to use the water with CONAGUA.

Competency Standards (abbreviated as ECO in Spanish) under development:

- "Implementation of the regulations, analysis and evaluation of treatment processes for wastewater agricultural reuse"
- EC0628 "Operation of WWTPs for agricultural irrigation" (developed, approved and published)
- "Control of irrigation systems with treated wastewater"

With the first Competency Standard (ECO) enforced, the certification process has been initiated (Figure 11), with work simultaneously taking place on two others, expecting to have the first certificate candidates by the second half of 2016, representing an important step in Mexico for the improvement of SUWA practices.

Figure 11: Certification of candidates during field exams at the SUWA WWTP in Acoculco

6. Summary, Conclusions, and Lessons Learned

- SUWA has demonstrated its outstanding importance for the current and future situation of water, food and the environment on the planet and for every country.
- Inertia to change exists for all SUWA proposals. Water and agricultural subsidies are obstacles to appreciating the value of treated water.
- Demonstrative pilot projects and capacity construction activities are the basic road towards the dissemination of SUWA practices.
- The Certification of Capacities and Competences of Irrigation with Treated Water is a necessary instrument to improve the acceptance of SUWA practices.
- The development of local and regional capacity building and certification processes through the seven institutions authorised nationwide are the immediate steps toward the technical and legal endorsement of persons qualified in the irrigation of treated wastewater, following WHO guidelines.

- The scheduling of regional workshops on SUWA practices at universities, agricultural unions and civil society organisations is an important side-step in this process.
- Preparing international workshops on WWTPs for SUWA purposes, successfully implemented in the states of Hidalgo and Oaxaca, will enable the sharing of important experiences and the recording of correct observations by UN agencies (UNEP, FAO, WHO, UNU, etc.), and will provide opportunities for progress in the safe use of treated wastewater in agriculture.

References

CONAGUA. 2001. "*Inodoros para uso sanitario-Especificaciones y métodos de prueba*" (in Spanish).

CONAGUA. 2015. "*Estadísticas del Agua en México*" (in Spanish).

CONOCER. 2008. "Registro Nacional de Estandares de Competencia" (in Spanish). Mexico.

Cooper, P.F. 2003. "Historical aspects of wastewater treatment". In *Decentralised Sanitation and Reuse*, 11–38. IWA Publishing.

Diario Oficial de la Federación. 2015. December 28. http://dof.gob.mx/.

European Food Information Council. 2014. "Farm to Fork."

Sanitation District of Los Angeles County. 2011. "Joint Water Pollution Control Plant."

Siebe, C. 1998. "Nutrient inputs to soils and their uptake by alfalfa through long term irrigation with untreated sewage effluent in Mexico." *Soil Use and Management* 13.

World Health Organization (WHO). 2000. "Guidelines for the microbiological quality of treated wastewater in agriculture: Recommendations for revising WHO Guidelines." *Bulletin of the World Health Organization* 78(9).

World Health Organization (WHO). 2006. "WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater." Geneva: World Health Organization.

CASE 17

The Reuse of Treated Water for Agricultural Irrigation in Bolivia (Bolivia)

Luis Grover Marka Saravia [1]

Abstract

Bolivia has 52.7 per cent basic sanitation coverage, but in many areas there are still no wastewater treatment plants and a large number of the existing ones do not function properly. This results in a potentially major source of pollution. In addition, there are currently no specific regulations for the reuse and management of treated wastewater for agricultural irrigation in place.

The Government of Bolivia is planning and establishing a regulatory framework to solve the problems related to the reuse of wastewater. To date, the only policies present are the Framework Law of the Mother Earth and Comprehensive Development for Living Well which defines guidelines for the treatment of water for extractive purposes, and the Economic and Social Development Plan (PDES) which outlines plans to refurbish and improve wastewater treatment plants with a focus on wastewater reuse.

Since 2009 the Joint Commission has promoted a series of activities aiming at capacity building programmes in Bolivia to define strategies and approaches to the problem of the reuse of treated wastewater for irrigation. These strategies will serve as a guide in developing a programme for the reuse of wastewater for irrigation in Bolivia within the framework of sustainable water management.

Keywords: reuse, agriculture, regulations, strategies, capacities

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1. Drinking Water and Basic Sanitation

At the national level, 80.8 per cent of the population in private dwellings have access to water and 52.7 per cent have basic in-house sanitation. Between the 2001 and 2012 censuses, access to water increased by eight percentage points (72.8 to 80.8 %), while basic sanitation coverage increased by 11 percentage points (from 41.4 to 52.7 %) (National Statistics Institute 2013).

In urban areas, 30 per cent of wastewater captured by sewerage systems is treated while the rest is discharged into receiving bodies. In Bolivia, 84 out of 98 municipalities with an urban population greater than 2,000 inhabitants have wastewater treatment plants (WWTPs) (Ministry of Environment and Water 2013a).

Thirty-one out of the 84 WWTPs do not function properly and the remaining 53 (more than half) have a removal rate of below 50 per cent. This means that the health of the population is at risk due to:

- Ageing of the WWTPs
- Inadequate budget for the proper management of the WWTPs
- Lack of operation and management (O&M) expertise by the plant operators

2. Irrigation and Reuse of Wastewater

According to projected estimates in 2012, only 32.5 per cent of the Bolivian population live in rural areas while the remaining 67.5 per cent in urban areas. This population requires a large quantity of food, safe drinking water and basic sanitation.

In Bolivia, 40 per cent of the national territory is in water shortage for irrigation purposes (more than seven dry months) and the effect of climate change is increasing uncertainty over the water availability for crops irrigation.

In 2012, only 11 per cent (303,000 ha) of cultivated land was equipped with an irrigation system and 70 per cent of irrigated land depended on abstraction from rivers (fluctuating flows). In Bolivia, approximately 7,000 hectares are irrigated with wastewater; 53 per cent of this area is in the city of Cochabamba (Ministry of Environment and Water 2013b).

Wastewater (treated or otherwise) is used as a renewable source of water for irrigation. Its use is often indiscriminate with no knowledge of the potential health effects that wastewater-irrigated crops might generate on final consumers.

It is estimated that there are approximately 13,400 industries in Bolivia, of which 94 per cent are small industries (1 to 10 employees) and 80 per cent of these industries are located in the cities of the central axis: La Paz, El Alto, Santa Cruz and Cochabamba (Bustamante 2002). Inhabitants of the lower basins have problems with water quantity and quality due to the human activities taking place in the upper basin that make use of high volumes of water and the returning of untreated wastewater to the freshwater ecosystem.

3. The Legal Framework for the Reuse of Treated Water

Bolivia has no specific regulations on the reuse of treated wastewater and management for agricultural irrigation. The environmental regulatory framework of the Law No. 1333 on water pollution states that the reuse of raw or treated wastewater by third parties has to be authorised by federal governments when the interested party demonstrates that reused water meets the quality established under the regulations (Plurinational State of Bolivia 1992).

Unfortunately, the water pollution regulation does not present a clear methodology for the classification of waterbodies. Each federal government ought to suggest a waterbodies classification in accordance to their suitability of use. To date, the lack of knowledge and facilities (laboratory analyses for basic parameters and the quality control of data) has limited this classification.

In October 2012, the Framework Law of the Mother Earth and Comprehensive Development for Living Well was enacted. This framework aimed at guaranteeing the continuity of the regenerative capacity of the components and systems of life of Mother Earth, recovering and strengthening local knowledge and ancestral learning in a framework of complementarity of rights, obligations and duties (Plurinational State of Bolivia 2012).

Among the rules and guidelines established include:

- Any industrial or extractive activity that involves the use of water shall, as appropriate, implement, among other things, proper extractive and processing dynamics that include treatment plants and/or processes that minimise the effects of pollution, as well as the regulation of the discharge of toxic waste into water sources.
- The regulation, protection and planning of the proper, rational and sustainable use, access to and exploitation of water resources, are exercised with citizen participation, establishing priorities for the use of drinking water for human consumption.
- The regulation, monitoring and control of the parameters and levels of water quality are observed.
- The promotion of the sustainable use and exploitation of water for food production is done in accordance with the priorities and productive potentials of the different areas.
- Adopting, innovating and developing practices and technologies are undertaken for the efficient use, capture, storage, recycling and treatment of water.

The Economic and Social Development Plan (PDES 2016-2020), within the framework of Comprehensive Development for Living Well of the Plurinational State of Bolivia, consists of:

- The strategic and prioritisation framework for goals and results
- Actions to be undertaken in the third term of government under the Democratic and Cultural Revolution, developed based on the Patriotic Agenda 2025 and the Programme of Government 2015-2020 (Plurinational State of Bolivia 2016).

On the issue of sewerage, the PDES establishes that by 2020, rural and urban areas should respectively attain 60 and 70 per cent of sewerage and sanitation services coverage, the minimum threshold established by PDES as acceptable levels of sanitation services and sewerage in Bolivia. Actions towards this goal have to include, among others:

- Expanding drinking water services in urban and rural areas through citizen participation, appropriate technology and the co-responsibility of the community in its use and maintenance.

- Developing concurrent strategies for environmental management and quality control of water for urban and rural human consumption, through implementation of the Water Quality Control Programme in Public Water Service Companies (PWSCs).
- Increasing sewerage and sanitation service coverage in urban areas with a focus on wastewater reuse (restricted cultivation and/or energy) and the co-responsibility of the population in the use and proper maintenance of the system.
- Increasing sewerage and sanitation coverage in rural areas with citizen participation and appropriate technology, while considering the culture of local communities.
- Refurbishing and improving wastewater treatment plants, with a focus on reuse (restricted cultivation and/or energy).

This decade has been established as the "Decade of Irrigation" (2015-2025) and plans are in place to incorporate the strategy for the reuse of water for agricultural irrigation to address the problem of climate change, in addition to establishing the following:

- Strengthening of the implementation process of the National Watershed Plan and the focus on the integrated management of water resources in inter-sectorial coordination processes and between the central Government and the Autonomous Territorial Entities
- Promotion of regional consultative platforms for the coordination of irrigation and integrated watershed management matters, with a focus on adaptation to climate change

4. The Joint Commission for the Reuse of Water for Irrigation

In Bolivia, the Joint Commission is an entity that provides space for the exchange of information, coordination and inter-sectorial consultation on priority issues. These issues have to contribute to the development of policies which aim at a proper management of WWTPs and sustainable reuse of wastewater for agricultural purposes. The Joint Commission was established in 2009.

Members of this Commission include the Vice-Ministry of Water Resources and Irrigation; the Vice-Ministry of Drinking Water and Basic Sanitation; Directors of the National Irrigation Service; the National Service for the Sustainability of Basic Sanitation Services (SENASBA), as well as representatives of the Gesellschaft für Internationale Zusammenarbeit (GIZ) programmes and other international cooperation bodies.

The Joint Commission, through the technical and financial support of GIZ, promoted the "Survey and Characterisation of Wastewater Reuse for Irrigation in Bolivia", with the objective of establishing draft sectoral strategies and guidelines.

Since 2011 the trilateral project "Supporting the Improvement of the Reuse and Treatment of Wastewater and the Protection of Water Bodies with a focus on Adaptation to Climate Change" has been implemented by Bolivia, Germany and Mexico to increase institutional and technical capacities for the promotion of wastewater reuse and to establish adaptation measures in the water sector to mitigate the effect of climate change.

In 2014, the collective commitment of the three countries generated a new trilateral project between Bolivia, Germany and Mexico called the "Reuse of Treated Wastewater for Agricultural Irrigation", which remained active until January 2016. This project intended to improve the management of treated wastewater for crops irrigation.

A summary of the results achieved (Ministry of Environment and Water 2015) during these two phases is presented in Table 1 below.

With the support of the World Bank, the potential of wastewater reuse for crop irrigation in Bolivia was analysed. The evaluation was based on the technical and economic analysis of two case studies in Cochabamba and Tarija. The results of these case studies showed that:

- There is great potential for the safe reuse of wastewater as a solution to the problem of water scarcity in semi-arid regions of the country and as an engine for their economic development.
- The stabilisation reservoirs demonstrated to be able to meet the quality requirements to permit a safe and unrestricted use of treated wastewater for crop irrigation. In this manner, wastewater reuse will optimise the use of water, maximise the cultivable land area and enable the simplification of operational and maintenance work in the WWTPs.
- It is necessary to overcome barriers that would jeopardise the long-term sustainability of the system (general discontent of resident population in the vicinity of the wastewater treatment plants in the country).

Table 1: Summary of the Results Achieved

Line of action	Results achieved
Legislation and regulation	• Draft of technical regulations on the reuse of treated wastewater for irrigation • A technical guide for the reuse of wastewater in agriculture • A guide to the selection and design of wastewater treatment projects
Capacity development	• Bolivian technicians were trained in Mexico and are applying their knowledge in the redesign of WWTPs • Bolivian technicians received training in monitoring and measuring water quality • A diploma in design criteria for reuse-oriented WWTPs jointly hosted by the Mexican Institute of Water Technology (IMTA) and the Higher University of San Andrés (UMSA)
Pilot projects for the treatment of wastewater for reuse	• Mexican advisors reviewed and made recommendations to two WWTPs design in Cochabamba city

Source: Ministry of Environment and Water 2015

As a next step, and with the support of the World Bank's Water and Sanitation Program, a study entitled "Socio-economic dimensions associated with the practices of wastewater reuse for productive purposes in the highlands" was undertaken to gather information on water reuse in agriculture and shape appropriate policy decision-making. The study promoted the reuse of wastewater in agriculture as (a) a climate change adaptation measure, (b) the sustainable use of water, and (c) the implementation of pilot projects in this field.

Farmers surveyed expressed willingness to collaborate in the management of the water treatment and distribution network, either by making monetary contributions or by devoting hours of work to the operation and maintenance of the system. Nevertheless, the financial contributions that farmers in these areas give to the irrigators' organisations remain very low. For this reason, despite the wish to collaborate, it will be necessary to define alternative and/or complementary mechanisms to ensure the financial stability of any already planned water reuse schemes.

The reduction of health risks through increased sewage treatment coverage and the improved performance of existing WWTPs are certainly needed. This calls for large investments in the refurbishment of these plants. The construction of new WWTPs is also compulsory but this will require a long-term implementation plan.

To counteract the risks inherent in the consumption of agricultural products irrigated with wastewater, complementary short-to-medium term impact measures are required, e.g. World Health Organization (WHO) measures (restriction of crops, localised irrigation, improved management of harvests, etc.).

The study confirmed the need for major efforts in the field of risk awareness and education of "safe water reuse management" for farmers, traders and consumers. Technical support for producers to support initiatives such as testing crops to be irrigated with reused water or marketing strategies for wastewater irrigated crops seems mandatory and therefore necessary.

5. Lessons Learned and Opportunities

5.1. Municipal Plans with an Emphasis on Treatment and Reuse

In Bolivia, the need for building treatment plants as an environmental requirement came about as compliance with the environmental recommendations that are part of the Law No. 1333. Unfortunately, so far there is no clear understanding on the use of treated wastewater as an important input for the irrigation of gardens or crops.

During this process, while the management of finance sustains the construction phase, there is no follow-up on the establishment of units capable to manage and operate wastewater treatment plants. Only for those municipalities in which the treatment of wastewater falls into their remit, it is possible to make the treatment obligatory and allocate resources for the operation and maintenance of treatment plants.

The quality of water in the outflow must be carefully monitored and controlled in Bolivia. This requires skilled laboratory technicians directly at the plant station which would at the same time improve O&M of the WWTPs.

5.2. Generation of Incentives for the Rational Use of Water and Reuse of Wastewater

To encourage the safe use of wastewater, it is necessary to change the way WWTPs and irrigated crops are given more importance. One way is to create incentives for good environmental practices. These incentives could depend on the type of reuse that domestic wastewater undergoes. It is important that these incentives are not included in the regular municipality budget. The establishment of a separate fund to reduce the economic and/or financial burden that may result from the design, construction, operation and maintenance of WWTPs is necessary. This fund could also be made available for industries that show good environmental practices so that the established rate can be subsidised.

5.3. Identification of Water Supply Alternatives

One of the problems that affect a large part of Bolivia is the increasing scarcity of water sources for drinking use. Climate change makes necessary the establishment of precautions on water supply especially for the bigger cities where the majority of the population is concentrated.

Bigger problems arise in areas of high population density where the federal capitals do not have water basins within their jurisdictions. This restricts them from making decisions in the area of conservation of water resources and any intent to search for water resources for human consumption has to be agreed upon on a case-by-case basis with those living in the place where the water is to be extracted.

In this context, the paradigm of competition for the use of water between drinking and irrigation can be changed in some cases by making them complementary, with treated wastewater advantageously replacing the water currently used for irrigation.

5.4. Establishment of Controls to Monitor Water Quality

So far, within the scope of Law No. 1333 on the environment, it has not been possible to establish any stable monitoring of waterbodies or discharges. The regulation of water pollution under Annex A of this law pertains to four categories of waterbodies depending on their fitness – 80 parameters with maximum permitted values in receiving bodies, and 25 parameters with permitted limits for water discharges.

With this high number of parameters to test, and in the absence of specialised personnel, the monitoring of discharges into water bodies becomes difficult, if not impossible.

As an alternative, it is possible to set up programmes at the universities for training environmental auditors and technicians for this purpose. Once trained, the specialised personnel are to return to their towns and start work in the WWTPs with guaranteed contracts, thus building capacities that can be developed at the rural level.

Moreover, to carry on effective water quality monitoring, the number of parameters to test have to be reduced to a manageable number, especially if the equipment and supplies available are limited. Reproducibility of the measurements is another essential requirement. This would allow for a time series comparison analysis and reliable results.

5.5. Intensive Promotion for a Proper Use of Sewerage and Wastewater Reuse Benefits

The existence of WWTPs is sensible only if there is a sewerage system which is capturing wastewater and conveying it into a common location. Building WWTPs in rural areas is usually a negative experience as poor management of sanitary systems and blockages of the sewerage network by various types of objects lead to intensive maintenance work which is not immediately available onsite.

Objections for the setting up of WWTPs are strong also from residents of areas close to the WWTP site. This is especially true when the plant is close to urban settlements and generates odours.

It clearly appears that wastewater cannot be reused without well-managed sewerage systems and functional treatment plants. The malfunction of one of the two parts would lead to poor water quality which would not allow for the safe reuse of water for irrigation.

It is necessary that, once the sewerage network is built, individual households have functional connections to it. To achieve that, public funding has to bear the costs of the household connections. Until now, wastewater treatment plants and their technologies have been difficult topics to introduce to society since no positive experiences have ever arisen from it. Full functioning pilot plants are therefore needed but above all, these plants have to be able to reduce odours produced by the WWTP sanitation process.

In addition to the technological efficiency, it is also essential that WWTPs be built with aesthetically acceptable architectural values for the area in which the plant will be built. This will help the inhabitants of the local area to better accept the infrastructure as part of the urban and peri-urban landscape.

5.6. Establishment of Health Goals and Multi-Barrier Water Treatment

In order to achieve a substantial improvement in the water quality in Bolivia and therefore the health of its citizens, multiple steps have to be taken. Both policy makers and technical operators have to work together to:

- Define and establish appropriate technologies and treatment levels for domestic wastewater
- Define irrigation techniques
- Define crops for which reused water irrigation should be restricted to
- Establish tests for human risk exposure for the consumption of crops irrigated with reused water

References

Bustamante, Rocio. 2002. "*Legislación del Agua en Bolivia*" (in Spanish).

Instituto Nacional de Estadística (National Statistics Institute). 2013. Press release. www.ine.gob.bo.

Ministry of Environment and Water. 2013a. "*Inventario Nacional de Sistemas de Riego 2012*" (in Spanish). Cochabamba: PROAGRO programme (GIZ).

Ministry of Environment and Water. 2013b. "*Sistematización Sobre Tratamiento y Reuso de Aguas Residuales*" (in Spanish). La Paz: PROAGRO and PERIAGUA programme (GIZ).

Ministry of Environment and Water. 2015. "*Informe del Taller de Evaluación de Medio Término (Report on Mid-term Evaluation Workshop)*" (in Spanish).

Plurinational State of Bolivia. 1992. "*Ley de Medio Ambiente* (Environment Act)" (in Spanish). Law No. 1333.

Plurinational State of Bolivia. 2012. "*Ley Marco de la Madre Tierra y Desarrollo Integral para Vivir Bien* (Framework Law of the Mother Earth and Comprehensive Development for Living Well)" (in Spanish). Law No. 300.

Plurinational State of Bolivia. 2016. "*Plan de Desarrollo Economico y Social 2016 - 2020 (Economic and Social Development Plan 2016 - 2020))*" (in Spanish).

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SAFE USE OF WASTEWATER IN AGRICULTURE: GOOD PRACTICE EXAMPLES

United Nations University Institute for Integrated Management of Material Fluxes and Resources (UNU-FLORES) promotes the Nexus Approach in managing three key environmental resources: water, soil, and waste. Wastewater management provides one of the best natural examples to demonstrate the usefulness of the Nexus Approach in managing these three resources. This book is an attempt to share what UNU-FLORES has learned from looking at examples across the globe on this subject. Seventeen interesting case studies gathered from around the world on wastewater reuse in agriculture are presented in this book. All cases provide first-hand information as they have been authored by the experts who implemented these cases or monitored the progress of them closely for years. The material is presented in three sections to improve readability. Section I presents five cases covering Technological Advances. Section II is dedicated for Health & Environmental Aspects and presents another five unique cases. With seven cases, Section III of the book provides a useful discussion on Policy & Implementation Issues.

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