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Comparative Effects of Secondary Treated Waste Water Irrigation on Soil Quality Parameters under Different Crop Types

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ABSTRACT

This study compares soil quality parameters, and salinity and heavy metal levels in soils cultivated with different crops under secondary treated wastewater irrigation in the Glen Valley, near Gaborone City, Botswana. The hypothesis being tested is that the impact of the wastewater on soil quality varies with soils and crop types. The study covers 4 selected crops, maize (*Zea mays* L.), spinach (*Spinacia oleracea*), olive (*Olea europaea*), and tomato (*Solanum lycopersicum*), most widely cultivated by the farmers. Three farm plots per crop type were sampled at 5 sampling points and at two soil depths, 0-15 and 15-30 cm. Samples were also collected at 5 sampling points from two control sites. Irrigation water samples were collected for microbiological analysis from 2 farms per crop type. The most significant differences and relationships are between those crop farms, such as maize and two of the spinach plots, with predominantly sandy soils (loamy sands - sand loams) on the one hand; and the olive, tomato and one of the spinach plots with sandy clay loams on the other. The importance of soil texture was confirmed by the strong correlations between the sand and silt contents, several soil quality parameters, heavy metals and other elements. With the exception of Cd and Hg, most soil heavy metal contents were lower on the irrigated plots than on the control plot. The EC values also show that soil salinity levels were still low on the irrigated fields, but SAR and ESP values were high. The secondary treated wastewater being used in the Glen Valley is biologically clean, but one recorded case of *E. coli* emphasizes the importance of avoiding sprinkler irrigation at all costs to protect human health.

Keywords: Glen valley, heavy metals, maize, olive, soil salinity, spinach, tomato

INTRODUCTION

In Botswana, the use of treated urban waste water for irrigation is a relatively recent innovation and although a number of studies have been carried out on various aspects of the system, knowledge is still limited on its impact on soil quality parameters. Emongor and Ramolemana (2004) gave a detailed review of the potential of the use of treated sewage effluent for horticultural production in Botswana. They reviewed some of the soil-related problems that may be associated with the use of sewage water for horticultural production. There are (a) physical problems related to soil clogging by suspended solids, soil drainage and soil aeration; (b) chemical problems pertaining to soil salinity and sodicity and the accumulation of heavy metals in the soil; and (c) possible biological problems associated with the persistence in the soil of pathogens and viruses that come with the sewage sludge. They concluded that, apparently because secondary treated water rather than raw effluent water is used in Botswana, few physical, chemical, or biological problems are associated with secondary sewage effluent applied to vegetables and fruits. These findings and views correspond to those of Wang *et al.* (2007) based on their study on treated wastewater effect on soil, crop and environment on the loess plateau in Dongzhi, China. Selim (2006) also noted that the use of treated wastewater had no detectable effects on soil quality in experimental fields in Egypt. Heidarpour *et al.* (2007) also found that in the arid environment of Iran, the use of treated wastewater for irrigation had more positive effects on the soil chemical properties than the use of groundwater. By contrast, in some parts of Africa, it has been found that large volumes of partially treated or untreated wastewater adversely affect both water bodies and the urban and peri-urban farmers using these water bodies as sources of irrigation. High levels of pollution, specifically microbiological contamination, have been measured in irrigation water and in crops (Keraita and Drechsel 2004). In spite of the favorable results from existing studies, Emongor and Ramolemana (2004) still emphasized the need for further studies in Botswana because of evidence from studies elsewhere that there is accumulation of heavy metals such as zinc (Zn), nickel (Ni) and chromium (Cr) in the food chain (Oloya and Tagwira 1996b) when sludge is used as a fertilizer for growing crops. Although most heavy metals end up in the sludge rather than in the wastewater, it is still necessary to carry out more studies to ascertain the benefits and limitations of wastewater on vegetables and fruit.

The views expressed by Cornish and Kielen (2004) are very pertinent here. In 1989 the World Health Organization (WHO) developed guidelines for the safe use of wastewater in agriculture, which were later revised based on new data from epidemiological studies, quantitative microbial risk assessments and other relevant information. But, Cornish and Kielen (2004) argued that a standard leading to 'no measurable excess risk' to health as stipulated in the WHO standards for wastewater used in irrigation was an unattainable and unhelpful medium-term goal under the conditions of indirect wastewater use seen in many cities. Instead, there was a need for explicit debate of the levels of risk that may be acceptable to individuals and communities, and the costs and benefits that they would bring with them. In other words, the issue of wastewater standards should be investigated at the level of each country and even each city or community. According to Cornish and Kielen (2004) "Informed debate, that is enabled to assess the risks associated

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with different water qualities and irrigation practice, may lead to the development of local water quality norms and wastewater management that account for the physical and social environments in which wastewater irrigation is actually practiced." Even in the revisions recommended in the WHO standards in 2000 the concession was granted that in specific cases, local epidemiological, sociocultural and environmental factors should be taken into account and the guidelines modified accordingly (Blumenthal *et al.* 2000). There is no evidence that the WHO standards have been updated since 2004 as emphasis seems to have been on the adoption of the WHO or other international standards with or without adaptation to suit local conditions (see WHO; CEHA 2006).

But, such local water quality norms cannot yet be easily formulated in Botswana today because there is scarce information on the use of sewage effluent (water) as a source of water for irrigation and on the possible accumulation of heavy metals on forage, cereals and horticultural crops especially vegetables and fruits. Khotlhao *et al.* (2006) analyzed Gaborone's secondary treated sewage water along the Notwane River for selected physical variables, anions and metal content to assess its suitability for crop irrigation. The generally high quality of the secondary treated water was attested to by the low levels of all the investigated metals and physical variables. All the physico-chemical variables were within the maximum recommended values for irrigation water except for the samples collected in March with a pH of 9.57 ± 0.009 against the recommended pH range (6.5-8.5). However, there were significant ($P = 0.05$) variations in the levels of the metals, and in pH and EC, between certain time periods and at different sampling points along the Notwane River. Indeed, it has been found that waste water used in irrigation varies widely in quality depending on the different cities from which it comes (Oloya and Tagwira 1996a, 1996b). These quality variations in urban waste water sources are yet to be properly documented in Botswana.

The risk of exacerbating soil salinity levels is one more reason why concerns have been expressed about treated waste water irrigation in a semi-arid environment like Botswana that has high rates of evaporation/evapotranspiration. Molatakgosi (2005) has shown that crops grown in saline environments show symptoms similar to those shown by drought-affected crops. In some parts of Botswana the use of saline water for irrigation, for example by cabbage farmers, is known to have contributed to a rise in soil salinity (Molatakgosi 2005). Is it possible that the use of secondary treated waste water might also lead to a rise in soil salinity levels? In addition to these concerns about the chemical health of the soil and crops, Emongor and Ramolemana (2004) stressed the need to determine the level of pathogenic helminths ova, protozoa, enteric viruses and bacteria in order to prevent the development of infectious diseases on sewage water users and horticultural produce consumers. The presence of pathogenic microorganisms in secondary sewage effluent creates the potential for disease transmission where there is contact, inhalation, or ingestion of the microbiological constituents of health concern. WHO (2006) noted that "in countries or regions where poor sanitation and hygiene conditions prevail and untreated wastewater and excreta are widely used in agriculture, intestinal worms pose the most frequently encountered health risks. Other excreta-related pathogens may also pose health risks, as indicated by high rates of diarrhoea, other infectious diseases, such as typhoid and cholera, and incidence rates of infections with parasitic protozoa and viruses. But in countries where higher sanitation and hygiene standards prevail, infrastructure for waste treatment is available and treatment processes are well managed, viral illnesses pose greater health risks than other pathogens. This is partly because viruses are often difficult to remove through wastewater treatment processes due to their small size, but also because of the resistance of some viruses in the environment and their infectivity at low concentrations. Additionally, people living in conditions where higher sanitation and hygiene standards prevail often have no prior exposure to viral pathogens and therefore have no acquired immunity and are more vulnerable to viral infection and illness."(p.10)

But, the issue of wastewater irrigation goes beyond the physical, chemical and biological quality of the wastewater and its variability. Equally important are the different types of crops being cultivated and the soils themselves. For example, it has been noted that the suitability of soils for receiving waste waters without deterioration varies widely, depending on their infiltration capacity, permeability, cation exchange capacities, and phosphorus adsorption capacity, water holding capacity, texture, structure, and type of clay mineral (Ivan and Earl 1972; Donahue *et al.* 1977). Sandy soils usually allow the greatest rates of water percolation but the least adsorption and sieving action. Clay soils high in smectite clay are most subject to structure breakdown when materials high in sodium salts are used. Phosphorus retention is greatest in well-weathered clay soils. Alkaline soils will remove most heavy metals by precipitation. Thus, there is a need for sustained studies in order to fully analyze and understand the long-term environmental impacts of the use of treated sewage water for crop irrigation. Li *et al.* (2001) had concluded that due to its low sodium adsorption ratio (SAR) the Gaborone sewage effluent was suitable for irrigation purposes provided the SAR did not increase with continued use to exceed 9. In a two-year experimental study in the Glen valley, Li *et al.* (2001) reported that the use of sludge and treated effluent increased maize yield by 8.62% compared to clean water. But, at the same time, there was an increase of sodium concentration in the top soil in excess of acceptable levels for crop production.

In their study in Jordan, Rusan *et al.* (2004) sampled sites irrigated with wastewater for 10, 5, and 2 years and a site not irrigated for soil and plant chemical analysis to evaluate the long-term effect of wastewater irrigation. They found that long-term wastewater irrigation increased salts, organic matter and plant nutrients in the soil. Indeed, plant essential nutrients such as total-N, NO_3, P, and K, were higher in plants grown in soils irrigated with wastewater. Soil pH, Zn, Fe and Mn were not consistently affected while soil Cu was not affected by wastewater at all. They also found that wastewater irrigation had no significant effect on soil heavy metals (Pb and Cd) regardless of duration of wastewater irrigation. Rusan *et al.* (2004) concluded that continuous irrigation with wastewater could lead to accumulation of salts, plant nutrients and heavy metals beyond crop tolerance levels. Leal *et al.* (2008) also noted that salt concentration in irrigated soils leads to clay dispersion clay particles to plug soil pores, resulting in reduced soil permeability. Therefore, these concerns should be essential components of any wastewater irrigation management. With proper management, plant growth, soil fertility and productivity could be enhanced through increasing levels of plant nutrients and soil organic matter. Indeed, for arid environments, Bhardwaj *et al.* (2008) found that replacing saline-sodic irrigation water with treated wastewater had beneficial effects on soil aggregate stability and hydraulic conductivity. In their own studies on the fertile loess plateau of China, Wang *et al.* (2007) found that crop yields were significantly higher in plots irrigated with treated waste water compared to non-irrigated plots. They also found that leachates at different soil depths did not show 'alarming levels' of constituents. For a period of approximately 14 months, the treated sewage irrigation had no significant effect on the loess soil and no cases of illness resulting from contact with the treated sewage were reported. However, there was a slight increase in the organic content of the soil on the plots irrigated with wastewater.

In Botswana, Ngole (2005) carried out greenhouse experimental studies to assess the suitability of the sludge generated at the Gaborone waste water treatment plant as a soil organic matter supplement in horticultural farming by examining its agronomic effects on selected soil types in the Glen Valley and other parts of Botswana. The study compared the effects of two types of sludge: Type 1, a 3-year old sludge and Type 2, a basically fresh 2-month old sludge. The sludge was applied at varying rates to four soil types taken from different parts of Botswana. The soil types comprised an Arenosol from Mmamabula, a Vertisol from Pandamatenga, and two Luvisols from Barolong and Tuli Block. Sludge application was found to have greatly improved the physico-chemical properties and the nutrient status of all soil types; the response was highest with the arenosol followed in order by the Luvisols and the Vertisol. However, Ngole found that addition of sludge also increased the numbers of faecal and total coliform linearly with rate of sludge application. But, significantly, faecal coliform numbers were drastically reduced over time during the crop growing period. Ngole also found that although the fresher Type 2 sludge had higher nutrient levels and lower metal concentrations than the older Type 1 sludge, metals were more labile in Type 2 than in Type 1 sludge. The risk of nutrient over application was also higher with Type 2 than with Type 1 sludge.

These findings, while very encouraging, still clearly point to the need for more studies in a place like Botswana that has recently adopted this innovation. This is in order to properly manage the wastewater irrigation system and its likely effects on soil quality and crop health and productivity. As Marschner (1995) noted about the Jordan River valley, for agricultural production in semi-arid Botswana, irrigation may increasingly have to rely on marginal waters, such as treated wastewater. The indications are positive subject to careful management. Hassanli *et al.* (2009) found that irrigation with effluent led to greater irrigation water use efficiency (IWUE) compared to fresh water, even though the difference was not statistically significant. But, Tabatabaei and Najafi (2009) noted that the use of municipal wastewater for irrigation needs special management in view of the environmental and health hazards. They experimented with different irrigation methods and found that subsurface drip irrigation gave the best results in terms of minimizing the environmental and health risks. Emongor and Ramolemana (2004) noted that most work with wastes and vegetables have been done with sewage sludge (e.g. Ngole 2005), and called for more studies describing the benefits and limitations of wastewater. Hence, this study is focused primarily on the effects of secondary treated waste water irrigation on soil quality parameters under different types of crops. The ultimate goal is to be able to recommend the most sustainable and environment friendly cropping systems for waste water irrigation in this semi-arid environment.

Thus the aim of this study is to analyze and compare soil quality parameters on farms where different types of arable crops are being cultivated under secondary treated waste water irrigation. The specific objectives are to sample soils on different farms and analyze them for soil quality parameters; analyze soil quality parameters in the uncultivated and non-irrigated parts of the study area with similar soils; assess soil quality changes on irrigated farmlands in relation to soil quality parameters in the uncultivated and non-irrigated lands; and compare soil quality parameters between different crops. The main hypothesis being tested is that the impact of treated waste water on soil quality parameters varies with the crop type.

MATERIALS AND METHODS

Study area

This study was carried out in the Glen valley, about 10 km northeast of Gaborone beside the Notwane River where about 234 ha of cropland are being cultivated with secondary treated waste water. The farms lie between the Botswana Defence Force camp and the Gaborone sewage ponds between latitudes (24º 35' 23.56" S and 24º 37' 01.14" S) and longitudes (25º 58' 43.29" E and 25º 58' 16.74" E). There are 47 different farms, varying in size from 1 to 10 ha being managed by private farmers raising a wide variety of arable crops. In addition, a government agency, the National Master Plan for Arable Agriculture and Dairy Development (NAMPAAD) is running a 13 ha farm for demonstration purposes to develop and introduce new technologies (mainly olive, alfafa/ lucerne) to the local farmers. The crops cultivated under waste water irrigation in the Glen Valley include tomatoes, spinach, okra, maize, cabbage, olive, lucerne, butternuts, and green pepper. The variety of operators and crop types provides a good opportunity for assessing the impact of different management systems on soil quality in the Glen Valley.

Being an alluvial-*cum*-colluvial landscape, the Glen Valley exhibits great variation in sediment and soil distribution. Patches of vertisolic clayey materials alternate with areas of more sandy and, even, gravelly deposits. Ground drainage conditions also vary with the micro-relief so that wet and imperfectly drained soils alternate with areas of good soil drainage at slightly higher elevations. The soils mapped on a scale 1:20 000 are classified as Luvisols, Lixisols, Cambisols, Calcisols, Regosols, and Arenosols. The Luvisols are the most extensive and include calcic, vertic and chromic subtypes. Lixisols are poorer occurrences of soils similar to the Luvisols. These soils are so intermixed in the valley that some farms straddle the areas of more than one soil type. However, texturally, Glen Valley soils are very similar irrespective of taxonomic classification.

Farm selection

The original plan was to sample farms according to soil types. But, this idea had to be shelved because of the intricate pattern of soil distribution in the valley with some farms having complex soil units. In the end the decision was taken to sample soils according to crop types irrespective of soil taxonomic classification. Particle size distribution would be used to test the similarity or dissimilarity between soils within and between crop types. In the choice of farms to sample it was decided to select farms that had been cultivated under irrigation continuous for at least 3 years to give a sufficiently long period for the impact of irrigation to begin to show. The preliminary investigations showed that certain crops have been highly favoured by the farmers and these are the ones that have enjoyed continuous cultivation for sufficient length of time. Thus, the following crop types were selected for study: olive, maize, spinach, tomatoes. It was easier to get the required number of samples for each of these crop types than for others. Constraints of time and money forced the decision to limit the number of farms per crop type to three.

Soil sampling

Five sampling points were selected on each farm. A systematic sampling framework was used in locating the sampling points. Since the crops were planted in rows, sampling points were selected along rows selected at intervals on each farm plot. In addition, 2 control sites were selected for soil sampling in the neighborhood of the Glen Valley farms. The soils were sampled at 5 sampling points in the control sites. Given the shallow rooting of the crops, soil sampling was limited to the top 30 cm of the soil at each point; the soils were sampled at 0-15 and 15-30 cm depths. Altogether, 10 soil samples were collected on each farm and control sites giving a total of 30 samples per crop type and control site. There were 150 soil samples in total analyzed in the laboratory.

Water sampling

Although the method of irrigation practiced on all farms is drip irrigation, this method is not strictly adhered to by some farmers. On some farms we noticed that the farmers basically used sprinkler irrigation. Drip irrigation is meant to reduce the health risks arising from the use of treated wastewater. But, since some farmers are not adhering strictly to the method, it was thought necessary to test the irrigation water itself for its microbiological health. Water samples were collected from one plot per crop type giving a total of 4 water samples. Topsoil (0-15 cm) samples were also collected from two plots per crop type and from two control sites giving a total of 10 soil samples. Both water and soil samples were analyzed for their bacteriological health as described below in the

Table 1 Analytical methods used for the determination of soil quality parameters.

Soil parameter	Method of analysis	Unit of measurement
pH	Potentiometric method in H_2O and $CaCl_2$	(-)
EC	Potentiometric method	µS/cm or dS/m
SAR	Sodium absorption ratio by derivation	SAR= Exch Na/√(Ca + Mg)
Particle size distribution	Bouyoucos hydrometer meter	% gravel, sand, silt, clay
Organic matter	Walkeley-Black wet oxidation method	% Organic matter = (% total carbon +1.72)/0.58
Available phosphorus	Olsen P	ppm
Available nitrogen	Kjeldahl	%
Exchangeable bases	Absorption spectrophotometer	Cmol/kg
Cation exchange capacity	Absorption spectrophotometer	cmol/kg
Exchange acidity	Exchangeable Mn, Fe, Al	cmol/kg
Base saturation	By derivation	BS = TEB/CEC x 100

section on microbiological analysis. The microbiological analyses were carried out in the Microbiology laboratory of the Department of Biological Sciences, University of Botswana.

Soil quality parameters

In agriculture and forestry, soil quality relates to the factors of soil organic matter, soil nutrient status, soil moisture relations, and soil tilth (physical state that enhances good soil aeration and drainage, seed germination and plant root growth and penetration). But, in the specific case of the Glen Valley where urban waste water is being used to irrigate farms in a semi-arid environment, there is need also to determine additional quality parameters particularly soil salinity and heavy metal content. Time and financial constraints would not allow inclusion of all relevant soil quality parameters in this study but the selected properties are indicative enough for the purpose of this study. The soil parameters analyzed or derived include: particle size distribution (sand%, silt%, clay%), pH, electrical conductivity, exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), soil organic matter, exchangeable bases (Ca^{++}, Mg^{++}, K^+, Na^+), exchange acidity (Mn, Fe, Al), cation-exchange capacity (CEC), total nitrogen (N), and available phosphorus (P). All the soil samples from the crop farms and control sites were analyzed for these soil properties. However, cost considerations lead to the restriction of the heavy metal analyses to a smaller number of soil samples. 52 soil samples were analyzed for Pb, Hg, Cd, Ni, Zn and Cu. 48 samples came from 2 soil depths at 2 sampling points per farm for each of the 4 crop types, while the remaining 4 samples came from the two control sites (1 sampling point per control site). All the soil chemical analyses, with the exception of total-N, were carried out at the physical laboratory of the Department of Environmental Science, University of Botswana. **Table 1** shows the analytical methods used for each parameter. Total-N was analyzed at the Department of Biological Sciences laboratory.

Microbiological analysis

14 samples (4 water samples and 10 soil samples) were examined for their microbiological health. Fresh samples were collected from the farm plots for microbiological analysis. The samples were collected in standard bottles for immediate analysis in the laboratory using stsnadard methods (ALPHA 1998; Mashad *et al.* 2009). The total viable count (TVC) was conducted by pour plate technique on plate count agar (PCA) and counting the colonies developed after the incubation at 37°C for 24 h (APHA 1998). The total coliforms were enumerated by the membrane filtration (MF) technique as described by APHA (1998). Enteric bacteria (e.g. *Escherichia coli*) isolation was done using selective or differential media (agar solutions) and identification was on the basis of the colonial, morphological and biochemical properties of the pathogens.

Data analysis

Simple descriptive statistical procedures (Mead 1996) were used to analyze the soils data. Data on soil parameters for each farm plot were averaged over the five sampling points. These average values are displayed graphically using compound line graphs to depict the variations from farm to farm and between crop types. Three measures were used to examine soil salinity levels on the farms. These were EC (µS/cm) (Van Reeuwijk 1993), SAR = Exch Na/√(Ca + Mg) and ESP= Exch Na/CEC x 100)(Singer and Munns 2006, p 264). The results are also shown graphically to show the comparison between the different crop types. A correlation matrix was produced, using Pearson's product moment correlation coefficients, to show the interrelationships between all the soil parameters analyzed for this study. This correlation matrix highlighted the influence of soil type on the effects of treated wastewater irrigation on soil quality parameters.

RESULTS AND DISCUSSION

Soil textural class

It was not possible to select farms on the basis of soil types because of the highly varied nature of soils in the Glen Valley. Indeed most farms straddle more than one soil type. Therefore, at the outset it was necessary to establish a firm basis for the comparative analysis of soil quality parameters between the different crop types. In order to do this, a comparison of the soil textural grades was carried out to ascertain if the soils belong in the same textural class or they are markedly different from one another. **Fig. 1** shows that texturally the soils are not too dissimilar; most soils are loamy sand or sandy loams. But, a few plots (spinach 3, olive, and tomato) have sandy clay loams with higher clay contents than soils on other farm plots. The crop farms appear to fall roughly into two groups; the maize and all but one of the spinach farms have higher proportions of sand compared to soils in the second group of crop farms made up of the olive, tomato and control plots. This apparent soil textural dichotomy between the two groups of crops is noteworthy because Wang *et al.* (2003) found that much of the variance in both the control and the reclaimed wastewater-treated fields they sampled originated from the variations in the soil physical attributes.

Soil pH

Wang *et al.* (2003) indicated that pH was among the parameters through which soil quality of reclaimed wastewater-irrigated fields and control fields could be compared. In this study, there is little variation in soil pH between the soils under irrigation (see **Fig. 2**). As to be expected pH in water is in all cases higher than pH in calcium chloride solution. But, the pH values indicate that generally the soils are slightly acidic to neutral in reaction. Almost everywhere, soil pH is higher on all the irrigated crop fields than in the control, the highest values being recorded on the spinach and tomato plots. Soil pH values are lowest on the olive plots and, except in one case, maize plots. Altogether, treated wastewater irrigation has had a positive impact on soil pH. This contrasts with the finding by Wang *et al.* (2007) which showed that wastewater irrigation lowered soil pH, though slightly, for example, from 8.39 pre-irrigation to 8.05 post-irrigation.

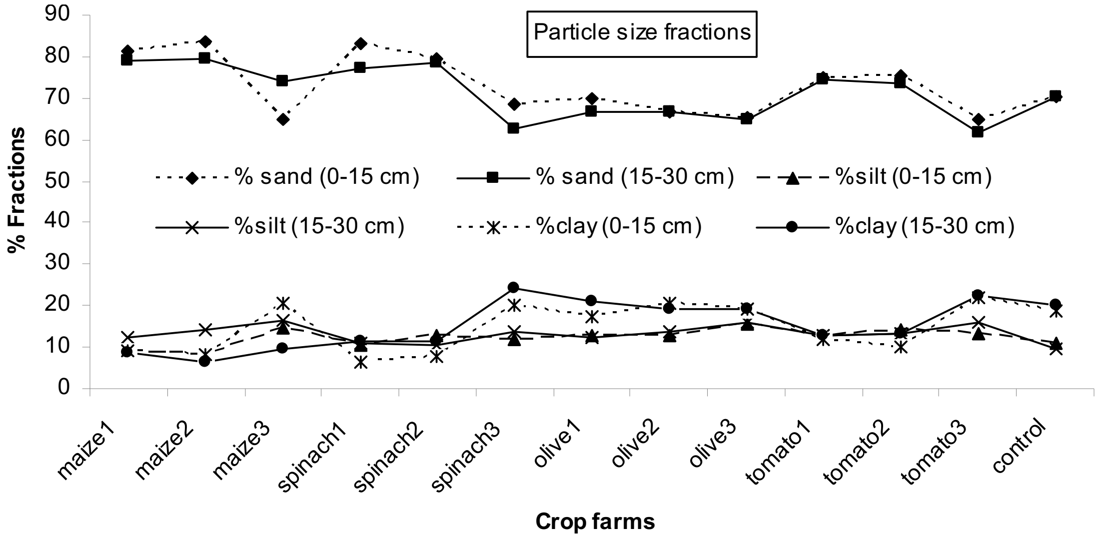

Fig. 1 Soil textural variation among soils being cultivated to different crops under treated wastewater irrigation in the Glen Valley.

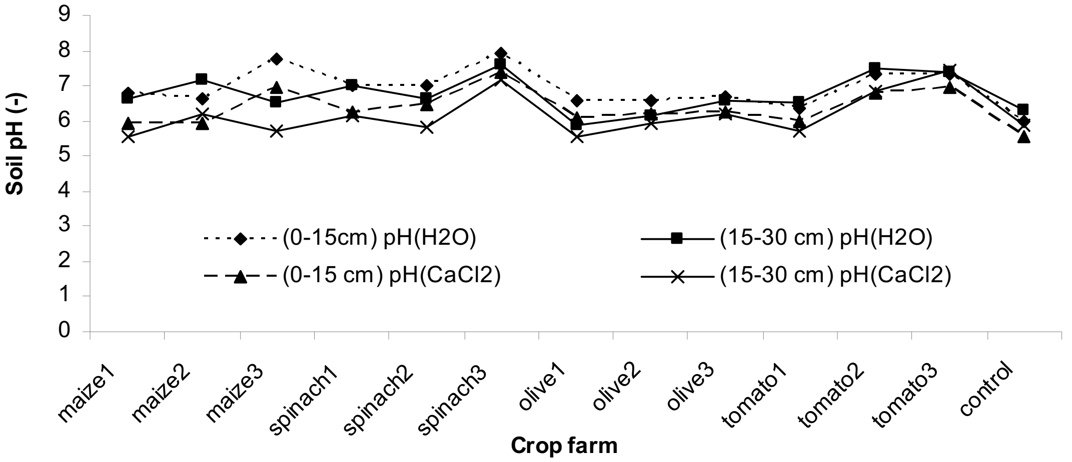

Fig. 2 Soil pH under different treated wastewater irrigated crops.

Soil organic matter and CEC and exchangeable bases

These soil quality parameters generally tend to improve under wastewater irrigation (Wang *et al*. 2003; Selim 2006; Wang *et al*. 2007; Tabatabaei and Najafi 2008). Soil organic matter levels are at their lowest under maize, even lower than in the control plots (**Fig. 3A**). Top layer organic matter levels are higher on spinach, olive and reach their highest levels on the tomato plots. There is greater variation between crops in subsoil layer organic matter content. Even so, the soils under maize still recorded the lowest values while the soils under olive and tomato fare better. Soil organic matter levels under spinach are about the same as in the control soils with the exception of farm number 3 which seems to differ from the two other spinach farms in almost all parameters. Soil organic matter content under olive and tomato is everywhere higher than in the control plots

Soil CEC varies very much between plots even under the same crop types (**Fig. 3B**). There are also marked differences between topsoil (0-15 cm) and subsoil (15-30 cm) CEC values. Except in a few sampling points, CEC values are higher in the subsoil than in the topsoil layers suggesting perhaps a higher clay-humus content and nutrient status in the subsoils than in the topsoils. Again soils under maize are little better than the soils of the control sites in terms of CEC at both soil depths, with values ranging 4-12 cmols compared to 4-9 cmols in the control plots.

In general, topsoils under spinach and olive have higher CEC values than under tomato and maize farms. But, in the subsoil layer, the highest CEC values were recorded on two of the tomato farm plots. The pattern of distribution and variation of the four major exchangeable bases (**Figs. 4A, 4B**) is the same as that of CEC. In almost all cases, the exchangeable base contents of the subsoil (15-30 cm depth) are higher than in the topsoil (0-15 cm depth). The graphs in **Figs. 5A** and **5B** also highlight the comparatively low concentrations of exchangeable Mg^{++} and Na^{+} in soils under all the different crops; exchangeable K^{+} appears to be the dominant exchangeable base, even higher than Ca^{++} in these wastewater irrigated soils except in respect of soils under tomato. This is contrary to the findings of Jalali *et al.* (2007) that irrigation using wastewater resulted in increased exchangeable Na^{+} on the exchange complex at the expense of exchangeable Ca^{2+}, Mg^{2+}, and K^{+}.

It is worth noting also that, it is only in respect of maize and spinach that the soils under irrigation appear to have levels of exchangeable potassium that are appreciably higher than that of the control site soils. With regard to all other exchangeable bases, there was no noticeable improvement in the soils under irrigation relative to the control site soils. But the soils of the 3 olive plots, 1 spinach and 1 tomato farm have higher soil exchangeable calcium than the control soils.

Available nutrients

Waste water irrigation appears to have enhanced the soil available P status on all the irrigated plots relative to the control site (**Fig. 5**). The topsoils under maize and spinach have the highest levels of available P. In the other crop plots, available P is much lower and seems to be more concen-

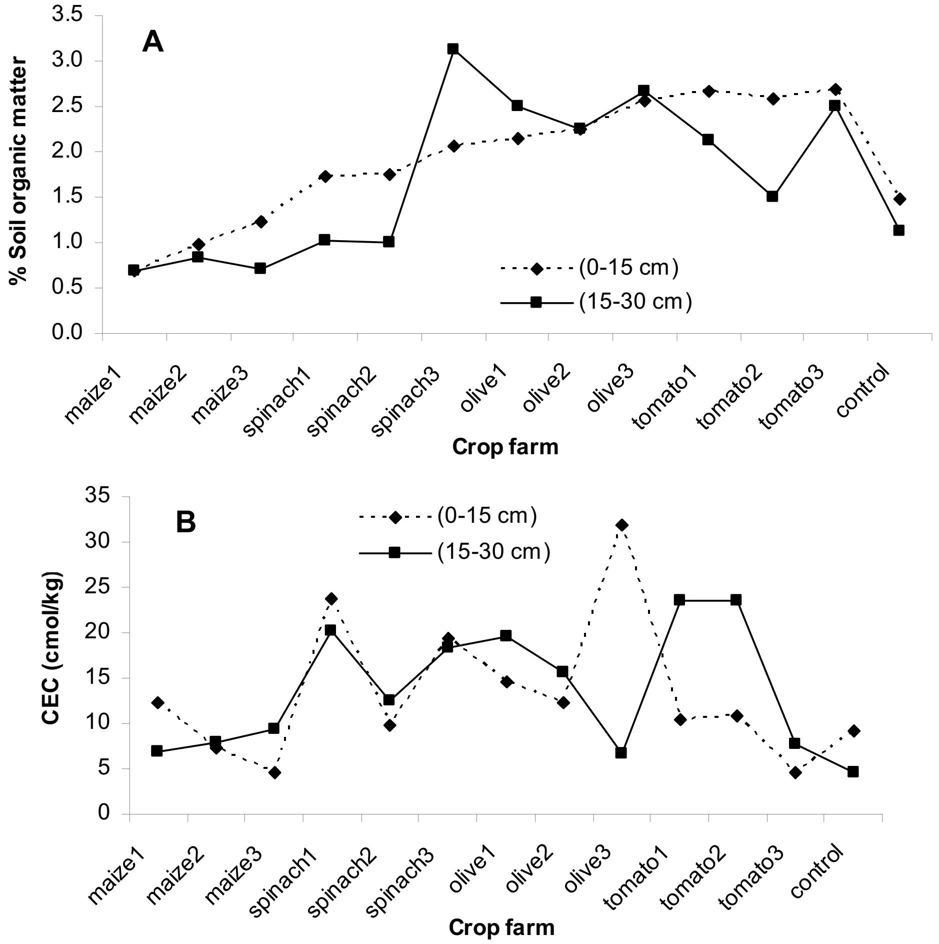

Fig. 3 Soil organic matter (A) and CEC (B) under different treated wastewater irrigated crops.

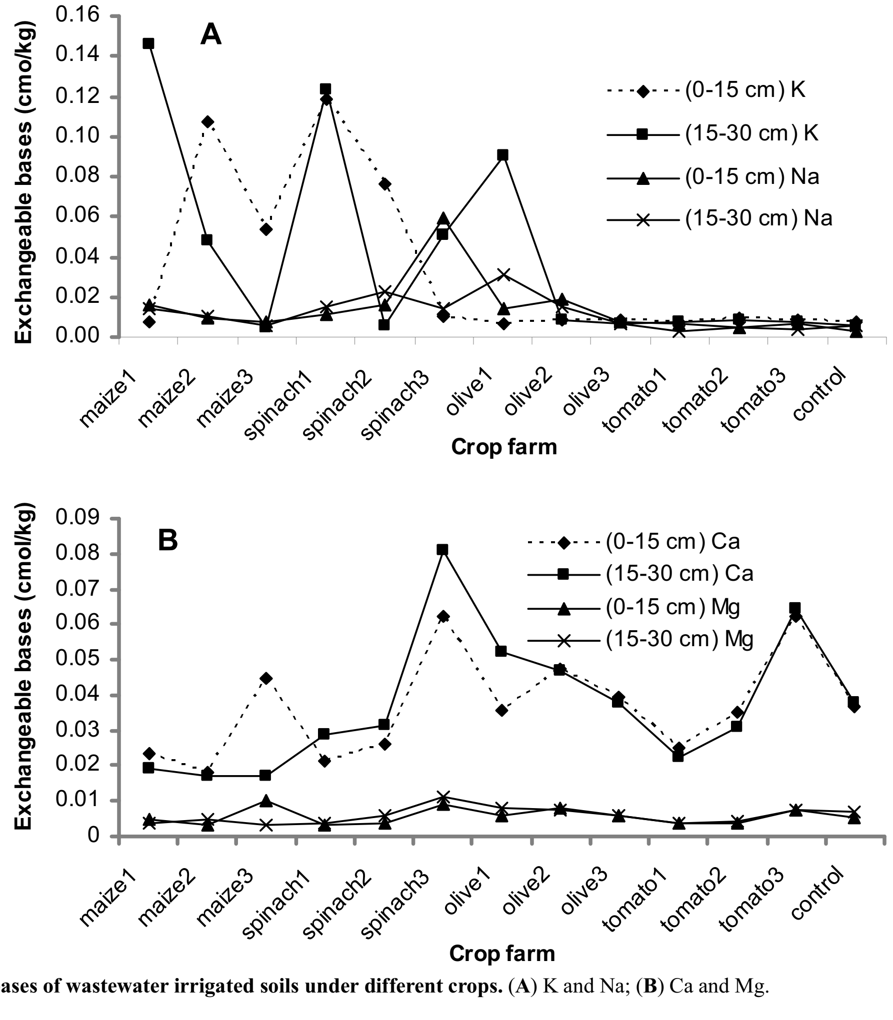

Fig. 4 Exchangeable bases of wastewater irrigated soils under different crops. (**A**) K and Na; (**B**) Ca and Mg.

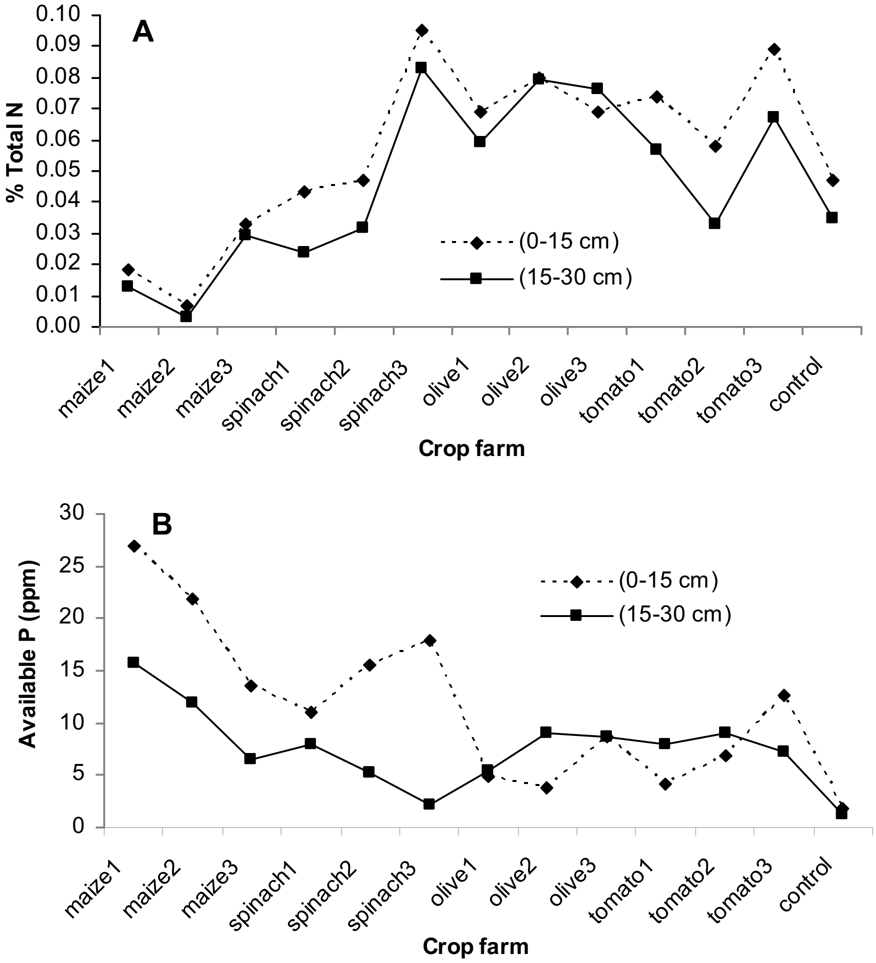

Fig. 5 Available nutrients. Nitrogen (**A**) and phosphorus (**B**) of wastewater irrigated soils under different crops.

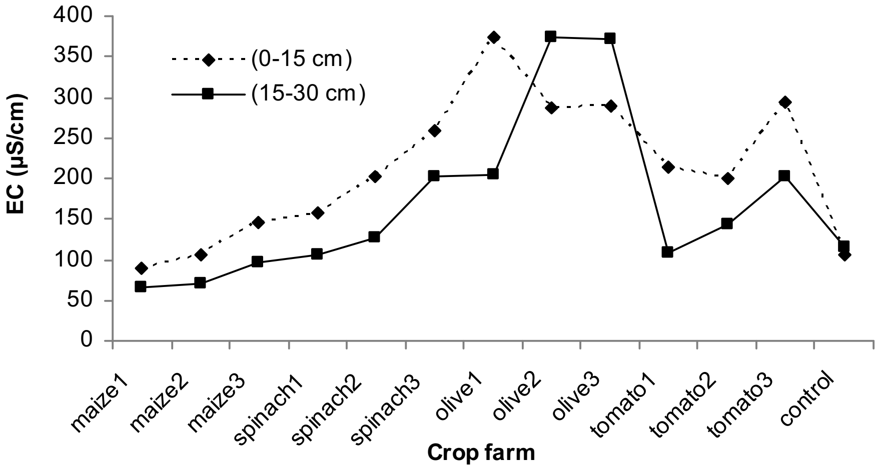

Fig. 6 Electrical conductivity (EC) of treated wastewater irrigated soils under different crops.

trated in the subsoil layer than in the topsoil.

Also apart from maize, and to some extent, spinach, wastewater irrigation has had positive effect on the total nitrogen status of the soils (**Fig. 5A**). These findings on the improved N, P and K nutrient status of the soils under treated wastewater irrigation are significant because the highly sandy soils (Arenosols) in Botswana are highly deficient in these important agronomic nutrients (Pardo *et al.* 2003) The highest levels of total-N are found in one of the spinach plots which significantly different from the two other spinach plots in almost every respect. Soil total-N on the olive and tomato plots are well above the level in the control sites (ranging from about 0.06-0.09%) whereas the reverse is the case on the maize and the two other spinach plots. Total nitrogen in the maize soils ranges from < 0.01 to about 0.033%; on the two spinach plots the range is roughly 0.024-0.047%.

Finally, the findings on the soil chemical properties seem to confirm the literature that vegetables generally do very well under surface or subsurface drip irrigation (e.g. Zotarelli *et al.* 2009). In general, soil chemical properties under maize are poorer than under the vegetables and olive.

Soil salinity

A major concern in irrigation in a semi-arid environment such as Botswana is the possibility of salt buildup in the soil (Schwiede *et al.* 2005). From **Fig. 6**, it is clear that soil salinity levels are still relatively low on all crop plots. Soils with EC levels of 2-4 dS/m are considered to be slightly

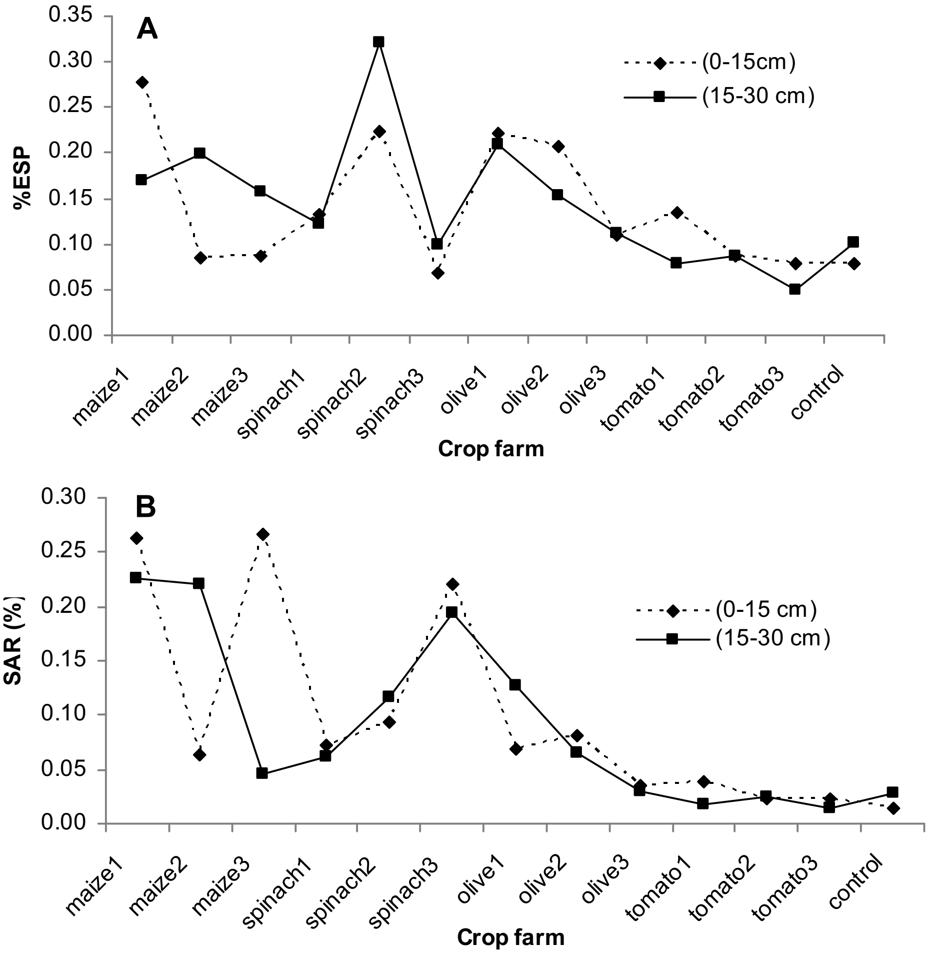

Fig. 7 Exchangeable sodium percentage (ESP) (A) and sodium adsorption ratio (SAR) (B) of treated wastewater irrigated soils under different crops.

Table 2 EC and SAR thresholds for different classes of saline soils

Soil salinity class	Threshold values of			
	pH	EC dS/m	SAR	ESP
Saline soil	<8.5	>4	< 13	<15
Saline-sodic soil	<8.5	>4	>13	>15
Sodic soil	>8.5	<4	>13	>15

Source: Compiled FAO/UNEP, 1984; Soil survey staff, 1987; Feiznia *et al.* 2001 from various sources

alkaline; 4-16 dS/m alkaline; while those with more than 16 dS/m are considered to be very strongly alkaline. The soils under olive and on some of the tomato and spinach farms fall largely in the 'slightly alkaline' class. The soils under maize and in the control sites fall below the 2 dS/m threshold for slightly alkaline soils.

It is quite possible that the ample rainfall received during the months prior to the soil sampling was partly responsible for these low levels of salinity.

The ESP and SAR produced similar results (see **Figs. 7A, 7B**). They indicate extremely low levels of sodium ion saturation in the soils (cf. **Table 2**). ESP identifies the degree to which the soil exchange complex is saturated with sodium while SAR gives information on the concentration of sodium relative to the combined concentrations of calcium and magnesium cations. There is very little danger of salinity in these soils at the present stage of secondary treated wastewater irrigation in the Glen valley. But, the long-term trend needs to be carefully monitored especially on the olive plots and to a lesser extent on the tomato and spinach plots. And, it is perhaps worth pointing out that the ESP and SAR values appear to be in an inverse relationship with EC values because the plots with comparatively higher ESP and SAR values are those with low EC values e.g. soils under maize.

Heavy metals and micronutrients

Table 3 gives the FAO threshold values for soil trace elements values for crop production. The heavy metal concentrations in the treated wastewater irrigated soils in the Glen valley (see **Figs. 8A-D** and **9A, 9B**) may be compared with these threshold values.

Judging from the threshold values indicated in **Table 3** above, the wastewater irrigated soils in the Glen Valley have higher than desirable levels of Cd, Ni, and Cu while the levels of Hg, Pb and Zn are lower than the maximum threshold values recommended for crop production. With specific reference to Hg, treated wastewater irrigation would appear to be less hazardous to the soil than that of treated biosolids commonly applied in the USA. Sloan *et al.* (2001) detected elevated Hg concentrations in soil and snowmelt samples from biosolids-treated agricultural soils following 20 years of biosolids applications.

It appears that the Glen Valley soils are naturally high in some of the heavy metal trace elements and that crop cultivation under wastewater irrigation has actually lowered the trace element content of the soils. This is true for example of Cu, Zn, Ni and Pb. It is only in respect of Hg and Cd that the control site soils fare better than the soils under cultivation. The somewhat high heavy metal trace element content of the soils may be due to their colluvial-*cum*-alluvial origin and the imperfectly drained ground conditions experienced during periods of high rainfall.

Comparing the crops, Cd and Hg levels are highest in soils under maize and decline linearly from maize to spinach to olive to tomato and control site. The pattern for the other heavy metals is broadly in the reverse order, with the lowest values being recorded in maize and then rising through spinach to olive, tomato to the control site soils. Thus, broadly speaking there seems to be an inverse rela-

Table 3 Recommended maximum levels of trace elements for crop production (FAO 1985).

	Element	Recommended maximum concentration (mg/l)	Remarks
Al	Aluminium	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
Cd	Cadmium	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Cu	Copper	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
Fe	Iron	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Mn	Manganese	0.20	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soils.
Ni	Nickel	0.20	Toxic to a number of plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pb	Lead	5.0	Can inhibit plant cell growth at very high concentrations.
Zn	Zinc	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.
Hg	Mercury	0.05	Toxic to many crops at pH 5-5.5

Source: Wastewater quality guidelines for agricultural use Series title: FAO Irrigation and Drainage Papers - 47 1992 T0551/E

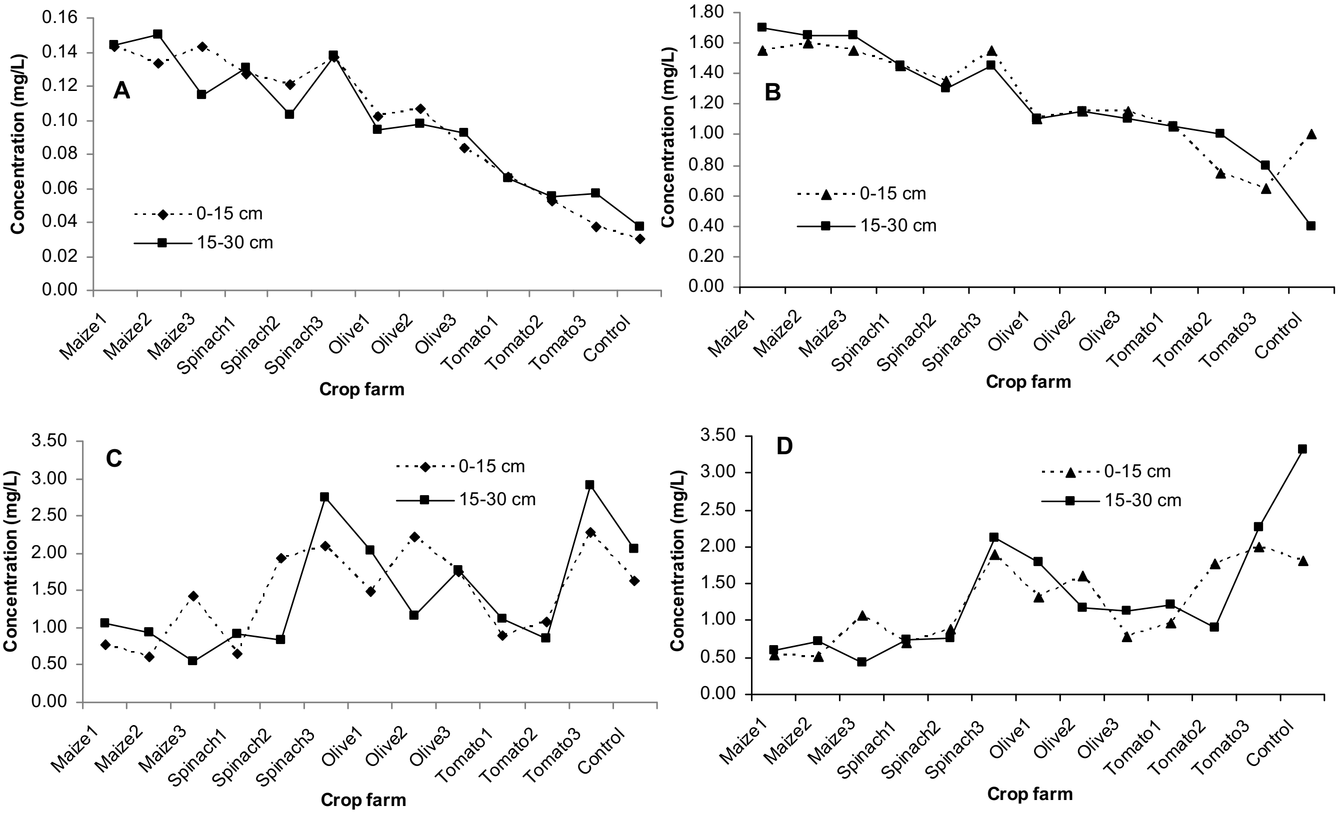

Fig. 8 Heavy metals in soils under different treated wastewater irrigated crops. (**A**) Cadmium, (**B**) mercury, (**C**) nickel (Ni) and (**D**) copper (Cu).

tionship between the concentrations of cadmium and mercury on the one hand and those of all the other heavy metals on the other. Soil pH and organic matter are the most critical factors in controlling Cd availability and plant uptake with low pH favoring accumulation (Barancikova *et al.* 2003; Kirkham 2006).

In general, wastewater irrigation appears to have raised the Al saturation levels of the soils under cultivation while lowering the Fe^{2+} and Mn levels. Al^{3+} levels are highest in the topsoils under olive and spinach (about 10-32 cmols/kg) while they are also high in the subsoils under tomato, olive and spinach. Al^{3+} levels under maize are about the same as in the control site soils (5-10 cmol/kg). However, it is only on four of the farms (2 tomato, 1 olive and 1 spinach) that Al saturation levels exceed the threshold maximum of 20 mg/kg (20 cmol/kg). Fe^{2+} and Mn vary widely between and among crop types but in general the highest levels are found under olive, tomato and spinach in that order. The Fe^{2+} and Mn saturation levels are everywhere well below the recommended maximum levels for crop production as indicated in **Table 3**.

Different flavonoid metabolic branches are total and faecal coliform counts

The water samples taken from four different farms are of an acceptable standard in terms of microbiological health. The total viable count in the water samples is in the range of 3 × 10^2-6 × 10^3/ml (**Table 4**), which is not bad for secondary treated raw water. Raw water for drinking purposes may have up to 10^2 bacteria/ml before chemical treatment (Tabatabaei and Najafi 2008). The water samples contain coliforms: 0.9-7.5 MPN/ml. All present are non-faecal coliforms which means that *E. coli* is not present.

With respect to the soil samples, their total viable count is normal to soils and indeed some of them appear very low indeed e.g. olive, tomato and control site. Why this is so is not clear but it is suspected that a low total viable count might be indicative of the presence of inhibitory chemicals in the soil. The coliforms in the soil are also non-faecal except the sample from one of the maize plots which contains *E. coli*. This would suggest that the microbiological health of the soils needs to be monitored continuously as a safe-

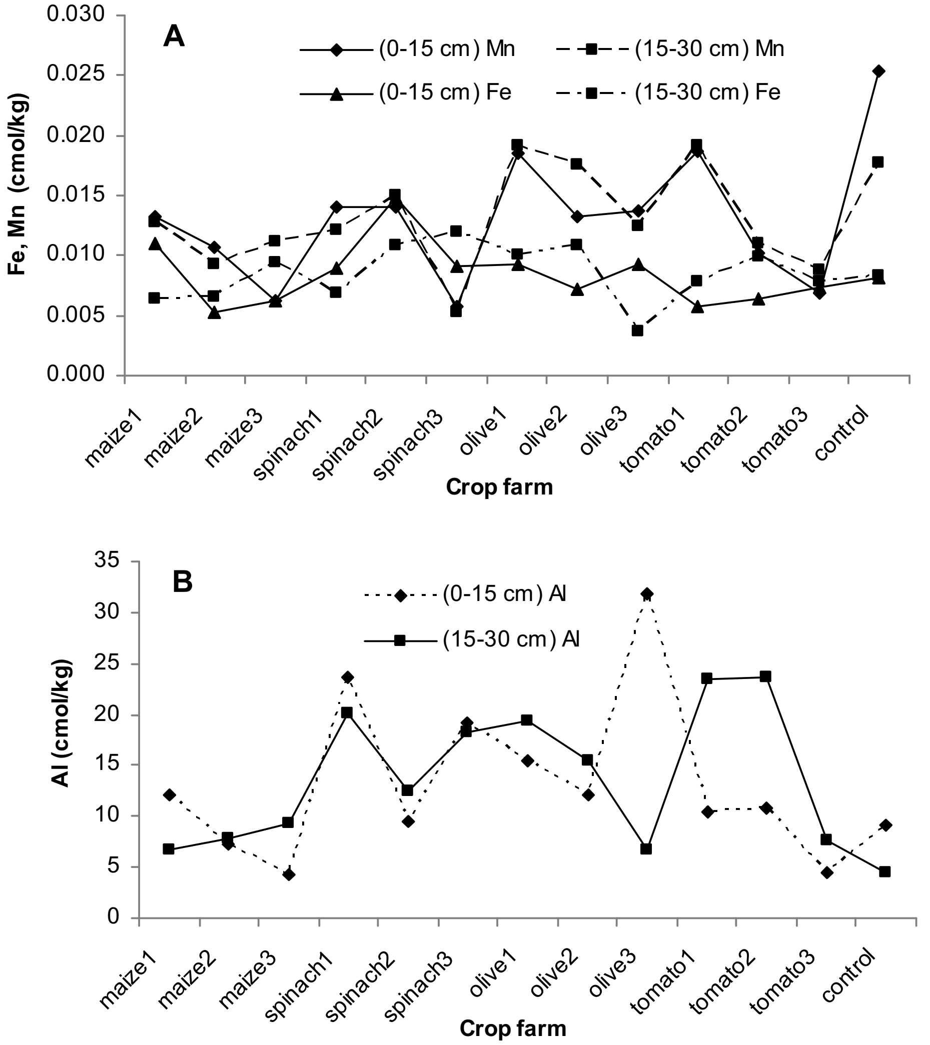

Fig. 9 Trace elements (Fe and Mn) (A) Al (B) in wastewater irrigated soils under different crops.

Table 4 Summary of total coliforms, TVC and *E. coli* from various soil and wastewater samples.

Sample	Total coliforms (MPN/g)	TVC (CFU/ml)	*E. coli*
Treated wastewater sample 1	7.5	5.75×10^3	-
Treated wastewater sample 2	4.3	1.15×10^3	-
Treated wastewater sample 3	0.9	1.63×10^3	-
Treated wastewater sample 4	0.9	3.2×10^2	-
Maize 1 topsoil sample	2.3	2.0×10^6	-
Maize 2 topsoil sample	0.9	2.68×10^5	+
Spinach 1 topsoil sample	15.0	1.74×10^6	-
Spinach 2 topsoil sample	›110	2.1×10^6	-
Olive 1 topsoil sample	1.5	2.4×10^5	-
Olive 2 topsoil sample	1.5	1.9 × 106	-
Tomato 1 topsoil sample	46	2.96×10^6	-
Tomato 2 topsoil sample	0.7	2.01×10^5	-
Control 1 topsoil sample	9.3	2.1×10^4	-
Control 2 topsoil sample	2.3	2.21×10^6	-

guard against disease for both crops and humans.

Intercorrelation between soil parameters

The table showing the correlation matrix between all the soil parameters will be found in the **Appendix** and only the major relationships are highlighted in the following discussion. Soil texture appears to be a strong factor in determining soil quality parameters under treated wastewater irrigation (see Wang *et al.* 2003). The soil texture grades have the highest number of other soil parameters significantly correlated with them. In this regard, it is interesting to note that the sand and silt contents exercise far greater influence on other soil properties compared to the clay content. In the top layer clay content has significant positive correlations with only EC (0.59) and organic matter content (0.68) top layer and total-N second layer (0.57). It is also significantly negatively correlated with K^+ second layer (-0.62) and silt content top layer (-0.70). In the second layer, clay is significantly negatively correlated with only top layer Mn (-0.68) and silt (-0.56) contents. In most cases sand and silt have inverse relationships with other soil properties. For example, sand content has strong positive correlations (>0.60-0.91) with EC, Mg, Ca, OM, Pb, Ni, Cu and N but these same soil parameters are all negatively correlated with the silt content. On the other hand, whereas sand has negative correlations with K (-0.61), P (-0.62) and Hg (-0.62), the silt content is positively correlated with the same soil properties even though some of the correlation coefficients are not statistically significant. It is possible that in the Glen Valley alluvial-*cum*-colluvial lowlands, the sandy nature of the soils promotes better soil drainage and aeration both of which have positive effects on soil organic matter and nutrient status, particularly on the sandy clay loams.

Organic matter (%) top and second layer, Mg second layer, K top layer, and Ca top and second layer are the soil nutrient status parameters most correlated with other soil properties. Organic matter shows statistically significant positive correlations with such other soil properties as EC, Mg, Ca, and total-N. Organic matter is negatively correlated with heavy metals Cd (-0.61 at both levels), and Hg (-0.75 top layer, -0.56 subsoil) while it is positively correlated with

Pb (0.58–0.65). Total-N has statistically significant positive correlations with EC (0.65–0.82), Mg (0.65–0.82), Ca (0.74-0.82), and OM (0.76–0.94), and with trace elements such as Pb (0.56–0.62), Ni (0.63–0.75), and Cu (0.57–0.70). It is negatively correlated with K in the top and second layers (-0.59,-0.62).

The importance of salinity is perhaps highlighted by the fact that it is highly correlated with as many other soil properties as organic matter and the exchangeable bases. EC has high positive correlations with organic matter (0.60–0.85), total-N (0.65–0.83) and sand% at both soil levels (0.59–0.71) and Mg (0.58), and Ca (0.67) at either the top or second layer. It also has high positive correlations with the heavy metals Pb (0.60) and Ni (0.60–0.66). The only negative correlations are with silt% at both soil layers (-0.59, -0.75).

CONCLUSION

Wastewater irrigation is relatively recent in the Glen Valley; indeed some of the crop fields have had less than 3 years of irrigation practice. Therefore, it may be too early for the impact of wastewater irrigation on soil quality parameters to fully manifest. Hence, the results obtained in this study should be regarded as tentative and only indicative of what might be in the future. Furthermore, it was discovered during the field work that none of the farm plots is used exclusively for any one crop; in fact the common practice is to use a farm plot for two or three crops in rotation during the growing season. Thus, these results may not truly reflect the effects of crop types; but they may be significant in pointing to the probable importance of textural differences between the soils in determining the impact of treated wastewater irrigation. The most significant differences and relationships appear to be connected more with soil textural class than with crop type. This is more so because texturally, the crop farms fall into two broad categories, those like maize, and two of the spinach plots with predominantly sandy soils (loamy sands - sand loams) and the olive, and tomato and one of the spinach plots with sandy clay loams. The importance of soil texture is confirmed by the strong correlations between sand and silt contents and several soil quality parameters and trace elements.

In terms of crops, there is a distinction between the maize and two of the spinach plots located on more sandy soils on the one hand, and all other crop plots (olive, tomato and one spinach) with slightly more clay + silt contents (sandy clay loams) on the other. Overall, soils under maize fared worse than soils under spinach, olive, and tomatoes in most parameters related to soil nutrient status including organic matter, total-N, CEC, and Ca. It is only in respect of P, and K that the soils under maize and spinach have higher levels than soils under the other crops. In terms of nutrient status the order of magnitude is: control site > tomato > olive > spinach > maize. The wastewater irrigated soils in the Glen Valley have higher than the recommended levels of Cd (≥ 0.01), Ni (≥ 0.20), and Cu (≥ 0.20) while the levels of Hg, Pb and Zn are lower than the maximum threshold values recommended for crop production. Indeed, Cd, Ni and Cu levels recorded in the Glen valley soils are close to or higher than the toxic levels for crops; these levels can become problematic at low pH values. Still, based on the present evidence, secondary treated wastewater irrigation would seem to have had more of a positive impact on soil heavy metal quality in the Glen Valley. This is because, as indicated above, with the exception of Cd and Hg, most soil heavy metal contents are lower on the irrigated plots than on the control plot. But, there are many unresolved questions that would require further investigation. Could the relatively lower levels of many of the metals in the soils under irrigation farming be due to higher rates of uptake by the growing crops? Do the comparatively higher levels of Cd and Hg in the soils under crop irrigation mean that there is a buildup of these elements in the soils? Only an analysis of the crop plants could help answer these questions.

Based on the EC values, soil salinity levels are still low in these treated wastewater irrigated soils. This may be due to the above average rainfall received in this part of Botswana and the high quality of the secondary treated wastewater. The highest levels of salinity occur on crop plots (e.g. olive) with sandy clay loam soils which might be due to the higher clay content compared to the loamy sands and sandy loams found on other crop plots. However, the correlation analysis shows a positive correlation between EC and sand content at both layers, clay content in the top layer and negative correlation with silt at both soil layers. However, the SAR and ESP may be more important than the EC values as measures of the salinization of these soils. These parameters indicate that even in soils with low EC values, the SAR and ESP values could be high. This study has shown that SAR and ESP values are higher under maize and spinach than under olive or tomato. The soils on which these crops are grown are among the most sandy in the Glen valley being mostly loamy sands and sandy loams. Finally, it is most important that farmers in the Glen Valley be monitored to ensure that they adhere strictly to the drip system of irrigation. This is important to ensure good crop health especially since the vegetables grown serve the urban market nearby. Although, analyses carried out in this study show that the secondary treated wastewater being used in the Glen Valley is biologically clean, one case of *E. coli* was recorded. For this reason, sprinkler irrigation should be avoided at all cost so as not to compromise human health.

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APPENDIX 1: Intercorrelation between the soil quality parameters.

A

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
pH(H2O)		**pH (CaCl2)**		**EC(µs/cm)**		**Mg(cmol(+)kg-1)**		**Ca(cmol(+)kg^{-1}**	
Layer 1	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
1.00	**0.63**	**0.95**	**0.55**	0.09	-0.06	0.50	0.20	0.51	0.32
	1.00	**0.62**	**0.84**	-0.17	-0.21	-0.06	0.15	0.26	0.27
		1.00	**0.69**	0.32	0.14	**0.58**	0.39	**0.70**	0.52
			1.00	0.25	0.20	0.22	0.49	**0.65**	**0.65**
				1.00	**0.73**	0.33	**0.58**	0.53	**0.67**
					1.00	0.40	0.49	0.52	0.51
						1.00	0.48	**0.84**	0.49
							1.00	**0.73**	**0.94**
								1.00	**0.81**
									1.00

B

11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Mn(cmol(+)kg-1)		**Fe(cmol(+)kg-1)**		**Al(cmol(+)kg-1)**		**K+(cmol(+)kg-1)**		**Na(cmol(+)kg-1)**	
Layer 1	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
-0.90	**-0.77**	0.04	0.38	-0.04	0.16	0.11	-0.02	-0.15	-0.08
-0.66	**-0.87**	-0.18	0.04	-0.01	0.14	0.20	-0.02	-0.48	-0.41
-0.85	**-0.70**	-0.02	0.46	-0.04	0.23	-0.07	-0.23	-0.23	-0.12
-0.59	**-0.73**	-0.20	0.13	0.02	0.08	-0.12	-0.25	-0.49	-0.37
-0.09	0.16	0.07	0.26	0.30	0.36	-0.44	-0.20	0.16	0.35
-0.06	0.11	0.03	0.00	0.50	0.00	-0.44	-0.34	0.20	0.08
-0.46	-0.24	-0.15	0.36	-0.12	-0.21	-0.38	-0.29	-0.07	-0.10
-0.13	-0.23	0.17	0.48	0.16	0.01	-0.38	-0.13	-0.06	0.29
-0.47	-0.38	-0.12	0.39	-0.05	-0.08	-0.52	-0.39	-0.27	-0.18
-0.23	-0.29	0.12	0.43	0.20	0.13	-0.43	-0.10	-0.12	0.19
1.00	**0.83**	0.13	-0.18	0.09	-0.02	-0.16	0.04	0.03	0.16
	1.00	0.09	0.03	-0.07	0.16	-0.25	-0.08	0.34	0.28
		1.00	0.14	0.26	-0.16	0.07	0.26	0.50	**0.59**
			1.00	-0.39	0.45	-0.13	-0.20	0.17	0.38
				1.00	0.14	-0.01	0.27	0.04	0.15
					1.00	-0.03	0.08	0.03	0.19
						1.00	0.24	0.17	0.17
							1.00	0.40	0.49
								1.00	**0.71**
									1.00

C

21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
CEC(cmol(+)kg-1)		**ESP**		**OM**		**Phosphorus(ppm)**		**Total Exch. Bases (cmol(+)kg-1)**	
Layer 1	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
-0.04	0.16	-0.30	-0.08	0.04	0.12	0.43	-0.10	0.34	0.09
-0.01	0.14	-0.57	-0.39	0.12	0.09	0.43	0.04	0.26	0.02
-0.04	0.23	-0.39	-0.20	0.31	0.37	0.21	-0.26	0.21	-0.02
0.02	0.08	**-0.62**	-0.54	0.46	0.47	0.09	-0.22	0.07	-0.03
0.29	0.36	0.10	-0.08	**0.76**	**0.85**	-0.45	-0.30	-0.24	0.13
0.50	0.00	0.04	-0.16	**0.60**	**0.72**	-0.42	-0.13	-0.24	-0.09
-0.12	-0.21	-0.22	-0.23	0.09	0.39	-0.06	-0.36	-0.05	-0.08
0.16	0.01	-0.16	-0.11	0.32	**0.74**	-0.11	**-0.61**	-0.12	0.29
-0.05	-0.08	-0.39	-0.45	0.45	**0.67**	-0.16	-0.48	-0.18	-0.07
0.20	0.13	-0.20	-0.30	0.50	**0.82**	-0.16	**-0.56**	-0.15	0.31
0.09	-0.02	0.28	0.09	-0.02	-0.13	-0.54	-0.21	-0.39	-0.02
-0.07	0.16	0.51	0.23	0.13	-0.06	**-0.64**	-0.07	-0.39	-0.13
0.26	-0.15	**0.60**	**0.62**	-0.17	-0.09	0.27	-0.11	0.09	0.36
-0.39	0.45	0.08	0.25	0.11	0.17	-0.15	-0.51	0.06	0.05
1.00	0.15	0.04	-0.12	0.26	0.40	-0.09	-0.02	-0.03	0.33
0.14	**1.00**	0.05	-0.13	0.50	0.30	-0.36	-0.12	-0.07	0.14
0.00	-0.03	-0.08	0.44	-0.46	**-0.58**	0.36	0.14	**0.92**	0.07
0.28	0.09	0.49	0.16	-0.50	-0.23	0.49	0.43	0.15	**0.90**
0.04	0.03	**0.88**	**0.68**	-0.26	-0.14	0.22	0.41	0.22	0.41
0.15	0.19	**0.68**	**0.73**	-0.20	0.05	0.10	-0.07	0.21	**0.64**
1.00	0.15	0.04	-0.12	0.25	0.40	-0.09	-0.02	-0.02	0.34
	1.00	0.05	-0.13	0.50	0.30	-0.36	-0.11	-0.07	0.15
		1.00	**0.61**	-0.25	-0.17	0.18	0.43	-0.14	0.45
			1.00	-0.47	-0.41	0.31	0.10	0.40	0.14
				1.00	**0.77**	**-0.64**	-0.31	-0.37	-0.28
					1.00	-0.36	-0.37	-0.39	0.11
						1.00	0.51	0.37	0.39
							1.00	0.01	0.15
								1.00	0.11
									1.00

D

31	32	33	34	35	36	37	38	39	40
Base Saturation		**Exch Acidity (cmol(+)kg-1)**		**Cd(mg/l)**		**Hg(mg/l)**		**Pb(mg/l)**	
Layer 1	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
0.48	-0.17	-0.04	0.16	0.39	0.34	0.22	0.47	-0.29	-0.42
0.47	0.04	-0.01	0.14	-0.02	0.15	-0.02	0.17	0.00	-0.12
0.62	-0.04	-0.04	0.23	0.16	0.12	-0.01	0.23	-0.08	-0.17
0.68	0.31	0.02	0.08	-0.32	-0.16	-0.38	-0.21	0.32	0.30
0.30	0.32	0.29	0.36	-0.21	-0.25	-0.45	-0.29	0.43	0.48
0.09	0.47	0.50	0.00	-0.19	-0.19	-0.32	-0.29	0.47	**0.60**
0.26	0.09	-0.12	-0.21	0.12	0.01	0.05	0.03	0.02	-0.01
0.10	0.08	0.16	0.01	-0.09	-0.04	-0.12	-0.28	0.33	0.40
0.54	0.30	-0.05	-0.08	-0.23	-0.25	-0.33	-0.29	0.36	0.36
0.30	0.19	0.20	0.13	-0.20	-0.15	-0.29	-0.33	0.44	0.49
-0.48	0.03	0.09	-0.02	-0.41	-0.44	-0.23	-0.56	0.21	0.41
-0.33	-0.07	-0.07	0.16	-0.29	-0.44	-0.28	-0.42	0.20	0.33
-0.17	-0.13	0.26	-0.16	0.27	0.20	0.22	0.10	-0.05	0.07
0.19	-0.67	-0.39	0.45	0.13	-0.05	-0.01	-0.02	-0.08	-0.06
-0.38	0.33	**1.00**	0.14	0.14	0.22	0.15	0.07	0.08	0.21
0.06	-0.40	0.14	**1.00**	0.00	-0.07	-0.17	0.03	0.06	-0.02
-0.17	-0.40	-0.01	-0.03	0.50	0.54	0.55	0.51	**-0.82**	**-0.63**
-0.52	-0.30	0.27	0.08	0.52	**0.62**	0.48	0.50	-0.15	-0.33
-0.37	-0.38	0.04	0.03	0.55	0.46	0.34	0.43	-0.09	-0.14
-0.39	-0.47	0.15	0.19	0.48	0.40	0.31	0.26	-0.21	-0.13
-0.38	0.33	**1.00**	0.14	0.14	0.22	0.15	0.07	0.08	0.21
0.06	-0.40	0.15	**1.00**	0.00	-0.07	-0.16	0.03	0.06	-0.02
-0.42	-0.29	0.04	0.05	0.37	0.28	0.21	0.27	0.11	-0.02
-0.34	-0.51	-0.12	-0.13	**0.56**	0.44	0.49	0.42	-0.51	-0.41
0.54	0.48	0.26	0.50	**-0.61**	**-0.61**	**-0.75**	**-0.56**	**0.58**	**0.65**
0.22	0.45	0.40	0.30	-0.29	-0.24	-0.40	-0.34	**0.59**	0.55
-0.14	-0.18	-0.09	-0.36	**0.66**	**0.77**	**0.65**	**0.76**	-0.32	**-0.61**
-0.17	0.06	-0.02	-0.12	0.32	0.42	0.21	0.53	0.05	-0.28
-0.02	-0.38	-0.03	-0.07	**0.56**	**0.57**	0.54	0.53	**-0.80**	**-0.59**
-0.41	-0.26	0.33	0.14	0.45	0.54	0.36	0.35	0.00	-0.13
1.00	0.32	-0.38	0.06	-0.50	-0.51	**-0.66**	-0.34	0.25	0.28
	1.00	0.33	-0.40	**-0.55**	-0.41	-0.51	-0.44	0.53	**0.56**
		1.00	0.14	0.14	0.22	0.15	0.07	0.08	0.21
			1.00	0.00	-0.07	-0.17	0.03	0.06	-0.02
				1.00	**0.95**	**0.92**	**0.94**	**-0.65**	**-0.80**
					1.00	**0.90**	**0.93**	**-0.56**	**-0.74**
						1.00	**0.84**	**-0.71**	**-0.81**
							1.00	**-0.61**	**-0.86**
								1.00	**0.84**
									1.00

E

41	42	43	44	45	46	47	48	49	50	51	52	53	54
Ni(mg/l)		**Zn(mg/l)**		**Cu(mg/l)**		**Nitrogen (%)**		**% silt**		**%Clay**		**%Sand**	
Layer 1	**Layer 2**	**Layer 1**	**Layer 2**	**Layer1**	**Layer2**	**Layer1**	**Layer2**	**Layer1**	**Layer 2**	**Layer 1**	**Layer 2**	**Layer 1**	**Layer 2**
0.23	0.08	0.30	0.06	0.21	-0.27	0.19	0.12	-0.20	-0.18	0.28	0.47	0.16	0.03
-0.06	0.21	0.28	0.22	0.23	-0.03	0.10	-0.07	0.19	-0.06	-0.14	0.23	-0.17	-0.01
0.45	0.27	0.30	0.04	0.44	-0.08	0.46	0.37	-0.40	-0.42	0.43	0.51	0.35	0.28
0.39	**0.58**	0.34	0.35	**0.61**	0.32	0.51	0.36	-0.25	-0.54	0.14	0.35	0.27	0.47
0.60	0.51	-0.29	0.02	0.41	0.24	**0.81**	**0.83**	**-0.59**	**-0.75**	**0.59**	0.31	0.51	**0.71**
0.66	0.36	-0.24	-0.13	0.32	0.18	**0.65**	**0.82**	**-0.65**	**-0.73**	0.54	0.40	**0.59**	**0.65**
0.66	0.38	0.51	0.12	0.49	0.23	0.44	0.54	**-0.83**	**-0.64**	0.42	0.56	**0.87**	0.50
0.74	**0.83**	0.33	0.08	**0.66**	**0.66**	**0.68**	**0.70**	-0.49	**-0.78**	0.06	0.02	**0.60**	**0.85**
0.82	**0.71**	0.52	0.22	**0.80**	0.50	**0.74**	**0.74**	**-0.83**	**-0.88**	0.45	0.49	**0.86**	**0.78**
0.74	**0.87**	0.30	0.19	**0.74**	**0.64**	**0.82**	**0.77**	-0.54	**-0.86**	0.18	0.11	**0.61**	**0.91**
-0.19	-0.03	-0.11	-0.24	-0.09	0.40	-0.10	-0.09	0.16	0.17	-0.18	**-0.68**	-0.15	0.06
-0.05	-0.23	-0.36	-0.33	-0.09	0.12	0.02	0.06	-0.02	0.14	0.12	-0.45	-0.04	0.01
0.27	0.03	-0.26	-0.26	-0.20	-0.06	-0.02	-0.01	0.20	0.12	-0.02	-0.48	-0.24	0.04
0.44	0.07	0.23	-0.34	0.56	0.16	0.36	0.25	-0.18	-0.17	0.12	-0.24	0.19	0.27
-0.02	0.14	-0.30	-0.24	-0.24	-0.06	0.24	0.36	-0.03	-0.25	0.16	0.03	-0.02	0.26
-0.19	-0.15	-0.30	-0.39	0.15	-0.18	0.39	0.23	0.16	0.01	0.20	-0.17	-0.26	0.05
-0.45	-0.50	-0.25	0.08	**-0.58**	-0.49	**-0.59**	**-0.62**	**0.63**	**0.63**	-0.43	-0.16	**-0.61**	**-0.63**
-0.53	-0.07	-0.16	0.31	-0.45	-0.24	-0.37	-0.37	**0.55**	0.33	**-0.62**	-0.32	-0.45	-0.25
0.05	-0.34	**-0.65**	-0.10	-0.40	-0.46	-0.16	-0.05	0.26	0.26	-0.19	-0.20	-0.25	-0.21
0.08	-0.01	-0.39	-0.09	-0.18	-0.10	-0.03	0.00	0.21	0.07	-0.19	-0.41	-0.19	0.07
-0.02	0.14	-0.30	-0.24	-0.24	-0.06	0.24	0.36	-0.02	-0.25	0.15	0.02	-0.02	0.26
-0.19	-0.15	-0.30	-0.39	0.15	-0.18	0.39	0.23	0.16	0.01	0.20	-0.17	-0.26	0.05
-0.08	-0.30	**-0.59**	-0.16	-0.40	-0.35	-0.18	-0.11	0.31	0.32	-0.17	-0.38	-0.32	-0.21
-0.04	-0.44	-0.44	-0.30	-0.49	-0.42	-0.45	-0.37	0.39	0.50	-0.18	-0.35	-0.41	-0.42
0.45	0.40	-0.21	-0.14	0.52	0.27	**0.85**	**0.76**	-0.49	**-0.64**	**0.68**	0.26	0.35	**0.60**
0.60	**0.74**	-0.02	0.01	0.53	0.45	**0.91**	**0.94**	**-0.62**	**-0.88**	0.44	0.34	**0.61**	**0.84**
-0.27	-0.13	0.00	0.28	-0.47	-0.44	-0.51	-0.47	0.46	0.39	-0.51	0.12	-0.37	-0.47
-0.55	-0.50	-0.51	0.22	**-0.62**	**-0.69**	-0.51	-0.44	0.47	0.49	-0.28	0.24	-0.48	**-0.62**
-0.14	-0.31	-0.14	0.17	-0.36	-0.41	-0.37	-0.38	0.36	0.36	-0.31	0.02	-0.33	-0.40
-0.17	0.27	-0.08	0.33	-0.14	0.02	-0.02	-0.04	0.31	-0.02	-0.50	-0.30	-0.19	0.13
0.43	0.27	0.19	0.31	**0.56**	0.13	0.41	0.23	-0.40	-0.37	0.53	0.42	0.29	0.26
0.27	0.48	-0.02	0.34	0.10	0.30	0.34	0.41	-0.47	-0.53	0.40	0.49	0.42	0.40
-0.02	0.14	-0.30	-0.24	-0.24	-0.06	0.24	0.36	-0.03	-0.25	0.16	0.02	-0.02	0.26
-0.19	-0.16	-0.30	-0.39	0.15	-0.18	0.39	0.23	0.16	0.01	0.20	-0.17	-0.26	0.05
-0.25	-0.41	-0.22	-0.12	**-0.59**	**-0.64**	-0.42	-0.29	0.34	0.40	-0.33	0.06	-0.29	-0.46
-0.33	-0.28	-0.22	0.06	**-0.61**	**-0.57**	-0.44	-0.31	0.44	0.37	-0.50	0.09	-0.34	-0.44
-0.34	-0.38	-0.04	-0.15	**-0.63**	-0.48	-0.54	-0.39	0.40	0.48	-0.49	-0.07	-0.31	-0.50
-0.41	-0.49	-0.26	-0.02	**-0.65**	**-0.79**	-0.49	-0.39	0.42	0.49	-0.30	0.23	-0.40	**-0.62**
0.37	0.54	-0.02	0.11	0.51	0.49	**0.60**	**0.56**	-0.34	**-0.55**	0.20	0.04	0.34	**0.59**
0.52	**0.56**	0.01	0.03	**0.59**	**0.65**	**0.62**	**0.58**	-0.42	**-0.61**	0.31	-0.13	0.39	**0.72**
1.00	**0.60**	0.22	-0.03	**0.67**	0.49	**0.71**	**0.75**	**-0.76**	**-0.77**	0.49	0.22	**0.75**	**0.77**
	1.00	0.42	0.43	**0.64**	**0.81**	**0.67**	**0.63**	-0.53	**-0.84**	0.06	0.12	**0.63**	**0.87**
		1.00	0.21	**0.58**	**0.59**	0.06	0.00	-0.38	-0.30	-0.06	0.03	0.50	0.32
			1.00	0.09	0.23	-0.08	-0.13	-0.06	-0.21	-0.33	0.29	0.18	0.12
				1.00	**0.72**	**0.70**	**0.57**	**-0.62**	**-0.73**	0.33	0.05	**0.65**	**0.78**
					1.00	0.50	0.43	-0.45	**-0.63**	-0.03	-0.25	**0.56**	**0.78**
						1.00	**0.94**	**-0.66**	**-0.85**	0.55	0.21	**0.62**	**0.86**
							1.00	**-0.76**	**-0.89**	**0.57**	0.33	**0.73**	**0.85**
								1.00	**0.84**	**-0.70**	**-0.56**	**-0.96**	**-0.72**
									1.00	-0.48	-0.42	**-0.86**	**-0.94**
										1.00	0.49	0.49	0.35
											1.00	0.51	0.10
												1.00	**0.76**
													1.00