Determination of inorganic pollutants and assessment of the current South African guidelines on permissible utilisation of sewage sludges

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Abstract

A total of 71 sludge samples originating from 61 sewage treatment works in South Africa were used in this investigation. Moisture, pH and total mineral ion content were determined. Moisture values were found to vary between 2.7% and 88.5% with the pH of the majority of the samples falling between 5.1 and 6.5. Mineral ion determinations showed that P was the most abundant in most of the sludges whereas, of the heavy metals, Zn had the highest concentrations and Cd the lowest. The current results (for 10 elements) were compared with the current South African maximum limits as stipulated in the permissible utilisation and disposal of sewage sludge for unrestricted use. The amounts of Cu, Se, Pb and Zn were found to be above the limit in more than 90% of the samples. No sewage works met the required limits for all the elements of interest. The results were also compared with the USA and EU limits, according to which all the elements were within the acceptable range and over 50% of the sludge samples met the required limits. These results suggest that the current South African limit is too conservative.

Keywords: sewage sludge, mineral ions, heavy metals

Introduction

Large quantities of sludge are generated in sewage treatment plants. The material is composed largely of highly polluting substances and it undergoes various treatments at sewage works in order to render it suitable for disposal or reuse. Among the most harmful components of sludge are pathogens (viruses, bacteria, protozoa and eggs of parasitic worms), toxic organic substances and toxic heavy metals (Bruce et al., 1989; Tchobanoglous and Burton, 1991; Smith, 1996). The adverse effects relating to heavy metals in the environment are due to their accumulation in the soil and in crops resulting in phytotoxicity, zootoxicity and harm to human health (Bern-Liebefeld, 1991; Rudd, 1987; Schmidt, 1997). The presence of major nutrients (nitrogen and phosphorus) that control biomass growth also plays a significant role in eutrophication-related problems when untreated or partially treated wastewater is disposed of and finds its way into water-bodies (Nhapi and Tirivarombo, 2004; Alastair et al., 1996; Jandu, 2004; Roy, 1996). The ultimate disposal of sewage sludge includes soil application, landfill, lagooning, incineration and disposal to sea amongst other options. Owing to the high concentration of many harmful substances present in sludge, many countries have banned disposal to sea. The disposal process continues to be one of the most difficult and expensive problems in the field of wastewater engineering (Tchobanoglous and Burton, 1991).

A well-treated sludge can be used as a nutrient source for vegetation. In South Africa an estimated 28% of the sludge generated at the sewage plants is used beneficially (Du Preez et al., 1999) whereas in countries such as Japan, the United Kingdom (UK) and USA, 42, 50 and 35% respectively of their sludge is used (Environmental Protection Agency (EPA), 1993). It is, therefore, clear that South Africa needs to improve its usage of sludge. This should include agricultural application for crop cultivation, soil reclamation in areas where mining activities take place and application in gardens. The beneficial usage of sewage sludge is a potential source of income to the sewage works and to farmers it could be a source of cheap fertiliser. Application of sewage sludge to land is restricted due to the presence of toxic organic substances and toxic heavy metals (Korentajer, 1991). The other limitation is the National Guidelines for the disposal of sewage sludge, which are sometimes very restrictive (WRC, 1997).

The aim of this investigation was to quantify the amounts of inorganic pollutants and phosphorus (as P) nutrients in sludge from 61 sewage works covering the 9 provinces of South Africa. The study provides much needed information on the quality of South African sewage sludge with regard to mineral ions. In terms of the bigger picture the paper assesses the current South African legislation (Guidelines) on permissible utilisation and handling of sewage sludges (WRC, 2002) by comparing the findings with the legislation and with the international limits, namely United States of America (USA) and European Union (EU). The information is expected to support decision making at national level.

Materials and methods

Collection and sampling of sludges

Sludge samples were collected from 61 wastewater treatment centres in the 9 provinces of South Africa, namely: Gauteng (GP), Mpumalanga (MP), Free State (FSP), Western Cape (WCP), KwaZulu-Natal (KZNP), Limpopo (LP), North West (NWP), Eastern Cape (ECP) and Northern Cape (NCP). The total number of samples collected was 71. At each sampling area a series of random samples was taken and mixed to produce a uniform composite sample. Glass containers with PTFE-lined closures were used for holding the samples. These were transported to the laboratory in an icebox at a temperature of approximately

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4°C maintained by using ice-blocks. They were then refrigerated at the same temperature until analysed.

Experimental procedures

Determination of moisture content

The solid sludge (approximately 100 g) was dried for 2 d in an oven set at 105°C. The samples were then cooled in a desiccator over silica gel before re-weighing to a constant mass. The moisture content of the sample was then determined as a percentage of the dry mass.

pH determination

The pH for solid sludge was determined by using the approach of Smith and Vasiloudis (1989) with slight modifications: 5 g of dried sludge was transferred into a 150 mℓ graduated cylinder to which 100 mℓ of MilliQ water was added. The solution was stirred on a magnetic stirrer for approximately 15 min until the sample was thoroughly dispersed. The pH of the solution was then measured using a Crison MicropH 2000 microprocessor-controlled pH meter equipped with a combined glass electrode. The electrode had previously been calibrated using standard buffer solutions of pH 4, 7 and 9 obtained from Sigma Aldrich.

Digestion of sewage sludges

Acid digestion of sewage samples involves the destruction of organic matter and dissolution of all inorganic forms of the mineral ions upon the use of acid. In this study, EPA METHOD 3050B was used (EPA Method 3050B, 1996). This method has been adopted by the USEPA as a standard method of extracting metal ions from samples and has been reported to have almost 100% recovery (Sims et al., 1991). During digestion, an accurately weighed 1 g sample of the previously dried and sieved solid sludge was used. The acids (all analytical reagent (AR) grade) used in this study were conc. HNO_3 (Fluka, 65%), 1:1 HNO_3 (v/v), H_2O_2 (Merck, 30%) and conc. HCl (Fluka, 30%). The samples were partially digested until foaming had reduced to a minimum and finally digested to completion by heating the mixture to a temperature of approximately 98°C on a steam bath for 3 h until the brown colour of the solution disappeared. During the course of digestion, each beaker was covered with a watch-glass upside down to reduce evaporation by acting as a condenser and to prevent the possible loss of metals through spitting. The mixture was then allowed to cool to room temperature (approximately 23°C) before filtering through a Whatman No. 41 filter paper into a 100 mℓ volumetric flask. The flask was filled to the mark using a 0.1 M HNO_3 solution followed by thorough mixing. The samples were then stored in polyethylene bottles ready for analysis. Four samples per sewage sludge were digested and analysed. Before use, all glassware and plastic-ware were washed with non-ionic detergent followed by dilute nitric acid (0.1 M HNO_3) and finally rinsed with MilliQ water.

Analysis of mineral ions

In the current study, inductively coupled plasma optical emission spectrophotometry ICP-OES (Varian Liberty AX150) was used. Wavelengths were chosen according to their freedom from spectral interference and calibration curve linearity. The ICP-OES was calibrated for each mineral ion with a suitable range of ICP standards all from Fluka chemicals, whereas phosphorus (dibasic ammonium phosphate) was from BDH (AR grade). Furthermore, to reduce the Easily Ionisable Elements effect (Hou and Jones, 2000) and to make sure that all the data points were within the calibration curve it was found necessary to dilute some of the samples. A 0.1 M HNO_3 solution was used throughout as a blank and for dilution. The instrument readings were converted into mg/kg. The values recorded represent an average of four readings per sludge sample.

TABLE 1
Mean pH value of sewage sludges with respect to the sludge types.

Sludge type	pH		No of samples
	Mean	Standard deviation	
Aerobic digested	6.1	0.3	3
Anaerobic digested	6.7	2.2	21
Compost	6.2	0.6	4
Digested sludge	6.0	0.6	13
Heated	7.0	0.7	2
Pellets	6.1	0.2	3
Petro™ sludge	5.9	1.6	3
WAS[a]	6.4	0.4	23
WAS[a] & digested	6.0	0.3	4

[a] WAS is waste activated sludge

Results and discussion

Moisture content and pH of sewage sludge

The results showed that the moisture content of the solid sewage sludges varied between a minimum value of 2.7% and a maximum value of 88.5% with a mean of 41.3%. The large range of moisture contents is not surprising since the samples were taken from many different sampling points within the different sewage works. Samples taken from the belt press or the centrifuge had very high moisture contents (>75%) whereas samples from bins, digesters and stockpiles were much drier (moisture content <20%).

The pH of the majority of the sewage sludges was found to fall between 5.1 and 6.5. The results are summarised in Table 1 according to the type of process.

Four samples had pH values between 4.7 and 4.9 (three anaerobic digested and one Petro™ sludge). These sludge samples are not ideal for land application or disposal as they are, since most crops grow best when the soil pH is between 6.5 and 7.0 (Knox et al., 2001). This means that the pH of sludge needs to be monitored and perhaps amended before sludge can be applied to land or stored in heap piles. It is also important to note that, although liming is crucial in increasing the pH of sewage sludge, over-liming can reduce the availability of major nutrients by binding them to the soil so that they become unavailable to the plant when the sludge is disposed of to land for agricultural purposes (Smith and Vasiloudis, 1989).

Mineral ion content

To compare the level of pollution in the different provinces, the values for the individual sludge samples for each sewage works in a province were combined and the mean value used to repre-

TABLE 2
The mean concentrations (± standard deviation) (mg/kg) of mineral ions per province

Elements	GP	MP[a]	FSP	WCP	KZNP	LP	NWP	ECP	NCP
[P] /10^4	9.8 (±5.4)	5.1	4.2 (±1.2)	5.5 (±3.1)	3.9 (±1.8)	4.0 (±2.0)	4.8 (±2.3)	3.4 (±1.8)	3.5 (±1.3)
[Ca] /10^4	7 (±11)	6.4	1.9 (±1.2)	3.5 (±4.1)	2.4 (±1.4)	2.0 (±1.5)	2.4 (±1.7)	3.6 (±4.7)	2.6 (±0.9)
[K] /10^3	11 (±19)	1.2	2.6 (±2.0)	2.9 (±2.4)	2.7 (±1.7)	2.5 (±2.6)	2.9 (±1.4)	2.0 (±0.5)	2.1 (±2.2)
[Mg] /10^3	8 (±8)	3.1	2.4 (±0.6)	4.1 (±2.1)	3.3 (±1.1)	3.5 (±1.9)	5.0 (±2.6)	3.8 (±2.8)	4.7 (±1.2)
[Zn] /10^3	**2.3 (±2.9)**	**1.2**	**1.0 (±0.1)**	**10 (±34)**	**1.3 (±1.5)**	**0.9 (±0.3)**	**1.4 (±0.7)**	**1.0 (±0.4)**	**0.8 (±0.1)**
[Cu] /10^2	**4.7 (±3.4)**	**4.3**	**2.2 (±0.7)**	**3.0 (±1.7)**	**45 (±135)**	**3.2 (±1.6)**	**5.7 (±8.4)**	**4.4 (±1.3)**	**2.7 (±0.9)**
[Cr] /10^2	**3.4 (±2.6)**	**1.9**	**0.6 (±0.2)**	**1.6 (±1.2)**	**13 (±37)**	**1.2 (±0.7)**	**25 (±64)**	**20 (±36)**	**0.4 (±0.2)**
[Pb] /10^2	**2.2 (±2.5)**	**1.8**	**1.7 (±1.2)**	**0.8 (±0.5)**	**15 (±45)**	**1.3 (±1.0)**	**1.4 (±0.7)**	**1.7 (±0.8)**	**1.1 (±0.4)**
[Se] /10^2	**2.2 (±3.6)**	**0.4**	**0.3 (±0.2)**	**0.9 (±1.5)**	**6 (±12)**	**0.9 (±1.6)**	**0.8 (±0.70)**	**2.5 (±1.6)**	**1.1 (±0.7)**
[B] /10^2	**0.3 (±0.2)**	**<DL**	**0.5 (±0.6)**	**1.4 (±1.0)**	**1.6 (±1.0)**	**1.5 (±1.5)**	**1.4 (±1.3)**	**2.2 (±1.2)**	**1.5 (±1.2)**
[Ni] /10^2	**1.1 (±1.3)**	**0.4**	**0.3 (±0.03)**	**0.4 (±0.3)**	**0.5 (±0.4)**	**0.4 (±0.2)**	**0.5 (±0.3)**	**0.7 (±0.2)**	**0.3 (±0.1)**
[Co]	**30 (±54)**	**12.7**	**13.5 (±4.6)**	**5.1 (±4.4)**	**11.3 (±9.6)**	**9.4 (±3.2)**	**12.9 (±7.1)**	**7.8 (±2.2)**	**5.1 (±3.0)**
[Mo]	**11 (±7)**	**7.5**	**7.9 (±1.7)**	**6.2 (±2.7)**	**9.8 (±5.0)**	**7.7 (±2.6)**	**8.7 (±3.1)**	**11.2 (±4.3)**	**6.5 (±2.4)**
[Cd]	**11 (±13)**	**2.8**	**2.5 (±1.2)**	**2.6 (±1.9)**	**6.7 (±10.4)**	**2.6 (±1.2)**	**3.9 (±4.2)**	**3.2 (±0.6)**	**1.7 (±0.8)**
No of samples	18	2	4	15	10	7	7	4	4
No of SW[b]	15	2	4	13	8	5	7	4	3

All boldface entries refer to mineral ions considered in the current South African guidelines (WRC, 1997)
[a] The standard deviation is not included since only 2 samples were analysed.
[b] SW = Sewage works

sent the quantity of that element. The standard deviation of the values was also determined. The results obtained are tabulated in Table 2.

These values have been arranged from the most abundant to the least. The results show that the content, the magnitude and the variability of mineral ions are approximately the same from province to province. A close look at the results reveals that Gauteng's sludge generally has the highest concentration of the mineral ions investigated. What is obvious from the table of results is the huge standard deviation associated with some elements. This points to the variable level of pollutants in different sewage works within the same province. It also indicates that the type of sludge received by individual sewage works may be very different.

Since the South African legislation covers only the major pollutants, these are indicated in bold-face in Table 2. The most common order of abundance is:

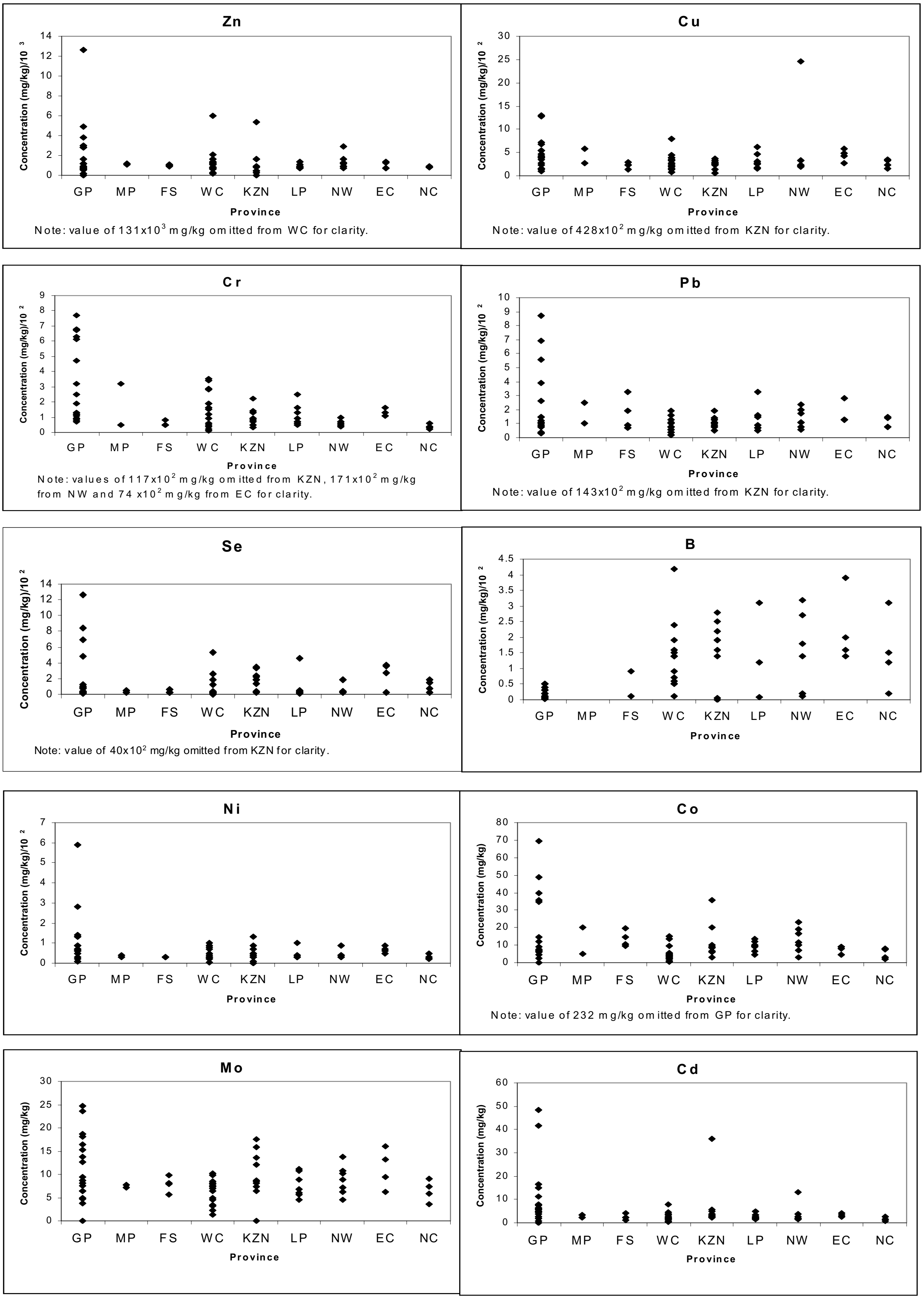
Zn> Cu> Cr> Pb> Se> B> Ni> Co> Mo> Cd

where:
Zn is the highest in concentration while Cd is the lowest.

The provincial average concentrations range from 2.3×10^3 mg/kg for Zn in Gauteng to 1.7 mg/kg for Cd in Northern Cape, a difference of 10^3 times in magnitude. It appears from Table 3 that the concentration variation between provinces is less than the within-province variation, thus indicating that there is probably not a significant difference in the average concentrations from province to province. However, it was considered inappropriate to perform a rigorous statistical test of this hypothesis (e.g. ANOVA) for two reasons. Firstly, the limited data set for many of the provinces – only two values for Mpumalanga and only four values for each of Free State, Eastern Cape and Northern Cape. Secondly, normal probability plots (Gardiner, 1997) of the concentrations obtained for each of the elements from Gauteng, Western Cape and KwaZulu-Natal showed that the data were not normally distributed within each of the provinces, with the possible exception of Mo (for which the correlation coefficients for the normal probability plots were 0.98 in each of the three provinces). Thus, in order to compare concentration variations within each province with variations between provinces, simple dot plots were constructed. In the dot plots, each dot on the chart represents one data point (i.e., one concentration value). These dot plots for each of the elements are shown in Fig. 1.

It can be seen from Fig. 1 that the variation between provinces is less than that within province variations for any given element. Also based on the data generated, it may be generalised that the sewage sludges produced in all 9 provinces are very similar in terms of their mineral ion type and abundance irrespective of the province (with the exception of a few exceptionally high values).

Because of this, it was considered appropriate to combine the individual sewage data from all provinces and calculate overall



Note: value of 131x10^3 mg/kg omitted from WC for clarity.

Note: value of 428x10^2 mg/kg omitted from KZN for clarity.

Note: values of 117x10^2 mg/kg omitted from KZN, 171x10^2 mg/kg from NW and 74 x10^2 mg/kg from EC for clarity.

Note: value of 143x10^2 mg/kg omitted from KZN for clarity.

Note: value of 40x10^2 mg/kg omitted from KZN for clarity.

Note: value of 232 mg/kg omitted from GP for clarity.

Figure 1

Dotplots of elemental concentrations in sewage sludge by element and by province

TABLE 3
The average concentrations (dry basis, mg/kg) of the different mineral ions in South African sewage sludges

Mineral ions	Mean	Median	Range	No of samples that were below detection limits
[P] /10^4	5.8	5.1	0.8 - 17	0
[Ca] /10^4	3.8	2.5	0.2 - 37	0
[Mg] /10^3	4.8	3.8	0.7 - 31	0
[K] /10^3	4.7	1.9	0.5 - 80	0
[Zn] /10^3	3.3	0.9	0.001 - 131	0
[Cu] /10^2	9.7	2.9	0.6 - 429	0
[Cr] /10^2	6.7	1.1	0.1 - 171	0
[Pb] /10^2	3.4	1.0	0.2 - 143	0
[Se] /10^2	2.0	0.4	0.06 - 40	1
[B] /10^2	1.1	0.8	0.002 - 4	11
[Ni] /10^2	0.6	0.4	0.1 - 6	0
[Co]	14.4	8.3	0.7 - 232	0
[Mo]	8.8	8.0	0.1 - 25	0
[Cd]	5.3	2.8	0.5 - 48	0

national averages. This was to provide a picture of the pollution status of the South African sewage sludge. The values generated on a dry mass basis are shown in Table 3.

It is shown that the range of concentrations is wide. This variation is possibly due to the different sources of pollutants that are received by individual sewage works. This is likely to depend on the type of industries that feed a particular sewage works and in the case of domestic sewage, it is likely to depend on the local population dynamics.

The high abundance of Ca can be attributed to the addition of lime to sewage sludge for stabilisation (George and Franklin, 1995) in addition to inputs from industrial and domestic sources. The top four (by abundance) mineral ions namely P, Ca, Mg and K are major plant nutrients. This means that South African sewage sludge is a potential source of these nutrients and may prove to be useful as a bio-fertiliser for agricultural applications.

A limitation facing its wider application for agricultural purposes is the presence of heavy metals. Among the pollutants of major concern in the South African guidelines, the following elements were found to be present in the sludges studied: Zn, Cu, Cr, Co, Pb, Se, B, Ni, Cd and Mo. The occurrence of these in sludge is of concern because of their possible adverse effects in the environment. Their order of abundance was found to be:

Zn> Cu> Cr> Pb > Se> B> Ni> Co> Mo> Cd

This order of abundance with respect to Zn, Pb, Ni and Cd is similar to that found in the USA based on a survey conducted by the Association of Municipal Sewerage Agencies under the USEPA in 1987 (Cecil et al., 1992). Similarly, this trend was also observed in the survey conducted by Smith for the inorganic chemical characterisation of South African municipal sewage sludges in 1989 (Smith and Vasiloudis, 1989).

If this sludge is disposed to land or used as a fertiliser, these metals are likely to be taken up by crops. Most soils, especially in the higher rainfall areas, are acidic or can easily be acidified because of poor buffer capacity (WRC, 1997). According to the current research data on pH, the sludge from the majority of the sewage works was found to have pH values of between 5.1 and 6.5. This means that the mobility of these metals in the environment and their availability to plants is possible, since these two factors are greatly increased when soil pH is 6.5 and below (WRC, 1997). The net negative effect of heavy metals on vegetation is plant poisoning by preventing their normal growth. Zinc, in particular, is a very common element in contaminated areas, even though a small amount of it is essential for plants growth (Werner, 1980). Therefore, apart from controlling the levels of the other heavy metals, the mobility of Zn needs to be controlled. Anderson and Christensen have shown that controlling soil pH is more important than any other single property in curbing Zn mobility (Anderson and Christensen, 1988). Moreover, Chaney also proposed that to prevent the excessive cadmium uptake by plants, the ratio of Cd:Zn should not exceed 1:100. The rationale being that zinc would become phytotoxic before cadmium is accumulated to excessive levels (Chaney, 1974). The South African sludge has a Cd to Zn ratio of 1:259, which means that plants are likely to die of Zn poisoning before accumulating high levels of Cd.

Comparison of 1989 and 2002 data

Comparing the concentrations of mineral ions within a period of 5 to 10 years is significant since it enables an assessment of changes in the level of the pollutants. This information equips the necessary government departments with scientific data that they can use to devise ways of controlling the levels by imposing certain regulations where necessary. Because of this, the current values were compared with the data obtained in 1989 (Smith and Vasiloudis, 1989). The concentrations of the mineral ions Ca, P, Mg, K, Zn, Cu, Cr, Pb, Se, B, Ni, Cd and Mo used in the comparison are shown in Table 3. Because the concentration values obtained in the 2002 study are not normally distributed, it is probably more appropriate to use the median values for comparisons.

Making reference to Table 4, the observation is that the concentrations of most of the major nutrients namely Ca, Mg and K did not change very much. The dramatic increase was for P, which increased more than threefold from a median value of 14 g/kg in 1989 to 51 g/kg in 2002. The possible source of this increase domestically is likely to be from laundry detergents.

However, on considering the heavy metals, the data show that the median concentration levels of Zn, Cu, Cr, Pb and Ni declined by between 21% and 51% between 1989 and 2002. Levels for Mo and Cd did not show any significant change between 1989 and 2002. The remaining mineral ions namely Se and B showed big increases from 2 and 28 mg/kg in 1989 to 41 and 80 mg/kg in 2002 respectively.

The concentration range for plant nutrients (P, Ca, Mg and K) has increased in the last 13 years, with the maximum values in 2002 being greater than 3 times those of 1989. The maximum values of the remaining species fluctuated with Cr, Se and B being higher in 2002 with the rest being higher in 1989. Based on the mean values, one can conclude that the quality of sewage sludge over the 1989 to 2002 periods did not change much. The exception being the levels of P, Se and B whose mean values increased by a factor of 3.

TABLE 4
Comparison of concentrations of mineral ions between 1989 and 2002 survey

	Mineral ions	1989[a] survey [*]			2002[b] survey		
		Range	Mean	Median	Range	Mean	Median
Conc (g kg^{-1})	**P**	4-41	16	**14**	8 - 170	58	**51**
	Ca	11-79	32	**29**	2 - 370	38	**25**
	Mg	2-13	6	**5**	0.7 - 31	5	**4**
	K	1-11	3	**2**	0.5 - 80	5	**2**
Conc (mg kg^{-1})	**Zn**	237-17 680	2 054	**1 432**	1 - 131 000	3 300	**900**
	Cu	80-17 217	654	**355**	61 - 42 900	970	**290**
	Cr	25-10 015	551	**220**	13 - 17 100	670	**110**
	Pb	67-10 137	452	**214**	18 - 14 300	340	**104**
	Se	1-107	4	**2**	6 - 4 000	200	**41**
	B	6-78	31	**28**	0.2 - 400	110	**80**
	Ni	6-2660	154	**55**	0.2 - 600	62	**42**
	Mo	1-24	6	**5**	0.1 - 25	9	**8**
	Cd	1-122	12	**3**	0.5 - 48	5	**3**

a - represents an average of 77 sewage sludge samples
b - represents an average of 71 sewage sludge samples.
Upper part refers to nutrient concentrations in g/kg and lower part to trace element concentrations in mg/kg
*(Smith and Vasiloudis, 1989)

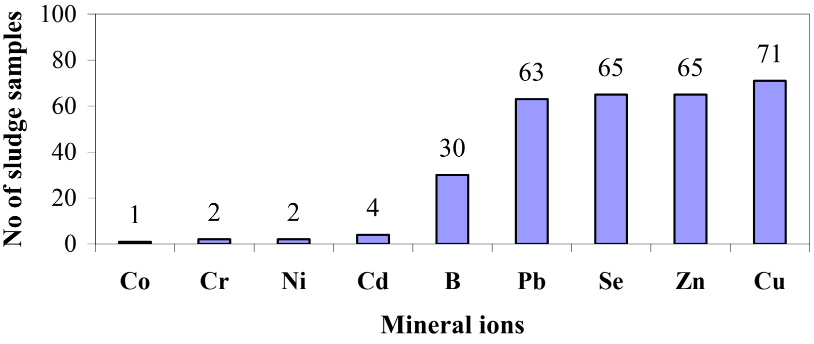


Figure 2
Number of sludge samples exceeding the maximum concentration limit of mineral ions as stipulated in the 1997 guidelines

Comparison of the current results with the existing South African guideline limits

The current South African legislation on permissible utilisation and disposal of sewage sludge was published in 1997 by the Department of Water Affairs and Forestry, the Department of Agriculture and the Department of Health. This document lists 13 elements and their maximum limits allowed for land application. In the 2002 survey, 10 of these mineral ions were determined and they are compared with the stipulated limits in Table 5. The national median concentrations for 4 out of the 10 elements exceeded the required limits (i.e. Se, Pb, Cu and Zn). When the 90th percentile values are considered then 5 out of the 10 elements studied exceeded the limits (B is added to the previous list). In order to have a broad view that links the individual sewage works and the maximum limits, Table 6 was generated (note that the sewage works have been given numbers for confidentiality reasons). This information is also summarised in a pictorial format in Fig. 2.

The results show that the concentration of Cu in the sludge was above the permissible limits in all of the sewage works and Se, Zn and Pb were above the limit in over 90% of the sewage works. In the case of B, almost half of the sewage works produced sludge that contained more than the permissible level of this element. Not even one wastewater treatment works met the requirements of the current guideline for unrestricted use in terms of the metal content. Snyman and coworkers (Snyman et al., 1999) also arrived at a similar conclusion.

It is hard to pinpoint single major contributors as the possible main sources of Cu, Zn and Pb pollution. This is because these elements, or compounds that contain them, are used in a wide range of industries as summarised in the literature (Conor, 1980; Stephenson, 1987; Trewavas, 1986). However, even though B and Se are used in a range of industries, one can speculate about their major contributors. This is likely to be the use of water softeners that normally contain B in the form of borax and the use of shampoos and lubricants that contain Se. Therefore, domestic effluents are likely to be the major source of the B and Se compounds that end up in the sludge.

In order to have an international perspective on the quality of South African sludge, the results of the current study were compared with the limits of the USA and the EU in Table 7. It is clear from the table that, except for Cr and Mo, South African limits are generally much lower than the USA and EU limits. This means that on average at national level (except for Se) all the elements that do not meet the current South African legislation requirement certainly do meet the USA and EU limits. If one compares the mineral ion concentrations for each of the individual sewage works sludges with respect to the USA and EU limits, over 50% of the sludges produced are within the limits according to the results of this study. This points to the fact that South African legislation on the unrestricted use of sewage sludge is too conservative.

Conclusion and recommendations

In conclusion, it can be stated that, based on mineral ion content and looking at the international limits, the quality of South African sludge is up to international standards. However, there is a need to control the pH of the sludge to restrict any possibility of heavy metal mobility. The study has also shown that the current South African legislation on permissible utilisation and disposal of sewage sludge is too conservative and tends to

TABLE 5
Comparison between the 2002 survey and the maximum inorganic limit in sludge (dry mass, mg/kg) permitted for land applications as in the current South African legislation

	Hg	Se	As	Cd	Mo	Pb	Cu	B	Co	Ni	Zn	F	Cr
Maximum-limits	10	15	15	15.7	25	50.5	50.5	80	100	200	353.5	400	1750
National median	-	40	-	2.8	8	100	290	80	8.3	40	9000	-	110
National 90th percentile	-	380	-	7.9	16	280	620	270	23	100	29000	-	630

TABLE 6
A list showing the sewage works in numbers and the respective metals that were found to exceed the current South African legislation guide, i.e. 1997 sludge guidelines

Plant no	Elements										Plant no	Elements									
	B	Cr	Cu	Se	Ni	Cd	Pb	Co	Zn	Mo		B	Cr	Cu	Se	Ni	Cd	Pb	Co	Zn	Mo
2			*	*		*	*		*		45	*		*	*			*		*	
3			*	*	*		*		*		46	*		*	*			*		*	
4			*	*			*		*		47			*	*			*		*	
5			*	*							48			*	*			*		*	
6			*	*	*	*	*	*	*		49			*				*		*	
7			*	*			*		*		50			*	*			*		*	
8			*	*			*		*		51	*		*	*			*		*	
10			*						*		52			*	*			*		*	
11			*						*		53	*		*	*			*		*	
13			*	*			*		*		54	*		*	*			*		*	
14			*	*			*		*		55	*	*	*	*			*		*	
15			*	*		*	*		*		56			*	*			*		*	
16			*	*			*		*		57			*	*			*		*	
17			*	*			*		*		58	*		*	*			*		*	
18			*	*			*				59	*		*	*			*		*	
19			*	*			*		*		60			*				*		*	
20			*	*			*		*		61	*		*	*			*		*	
23			*	*			*		*		62	*		*	*			*		*	
24			*	*			*		*		63	*		*	*			*		*	
26			*	*			*		*		64			*	*			*		*	
27	*		*	*			*		*		65	*		*	*			*		*	
28			*	*			*		*		67	*		*	*			*		*	
29			*	*			*		*		68			*	*			*		*	
30	*		*	*			*		*		69			*	*			*		*	
31			*	*			*		*		70			*	*			*		*	
32	*		*								71	*		*	*			*		*	
33	*		*						*		72	*		*	*			*		*	
34	*		*						*		73			*	*			*		*	
35	*		*	*			*		*		74	*		*	*			*		*	
36	*		*	*			*		*		75	*		*	*						
37			*	*							76	*		*	*			*		*	
38			*	*			*		*		77			*	*			*		*	
39			*	*			*		*		78	*		*				*		*	
40	*		*	*			*		*		79	*	*	*	*			*		*	
41			*	*		*	*				80	*		*	*			*		*	
44	*		*	*			*		*												

NB: Plants no. 1,9,12,21,22,25, 42 (liquid samples) have been omitted. Plants ~~no~~ No 43 & 66 were not sampled
Note that some of the sewage works have been sampled at more than one sampling point. The paired numbers belong to the same sewage works: (2,3), (10,11), (19,20), (33,34), (45,56), (46,47), (51,52), (58,59), (62,65) and (67,68).

TABLE 7
Comparison of maximum inorganic limit in sludge (dry mass, mg/kg) permitted for land applications in the current South African legislation (1997) and the international limits

Elements	SA[1]	USA[2]	EU[3]	SA national mean[4]
Cd	15.7	39	20 - 40	5.4
Co	100	-	-	14.5
Cr	1750	1 200	795*	280
Cu	50.5	1 500	1 000 - 1 750	370
Hg	10	17	16-25	-
Mo	25	18	20*	9
Ni	200	420	300 - 400	61.5
Pb	50.5	300	750 - 1 200	150
Zn	353.5	2 800	2 500 - 4 000	1 400
As	15	41	32*	-
Se	15	36	25*	140
B	80	-	-	90
F	400	-	-	-

[1] (WRC, 2002)
[2] (Sultan and Rahman, 2001)
[3] (Eliot, 2003)
[4] The national mean concentrations of mineral ions taken from Table 2.
* Mean of recommended values for European Community (Webber et al., 1983)

prevent the use of sludge for beneficial purposes. The government should rethink the current limits in view of the international limits. This will in turn encourage the use of sludge for beneficial purposes.

Furthermore, there is a need to control the amount of phosphates and all P-based compounds that end up in the sludge to avoid the danger of eutrophication in the environment.

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References

FERGUSON AJD, PEARSON MJ and REYNOLDS CS (1996) Eutrophication of natural waters and toxic algal blooms. In: Hester RE and Harrison RM (eds.) *Agricultural Chemicals and the Environment.* The Royal Society of Chemistry, London. 27-41.

ANDERSON PR and CHRISTENSEN TH (1988) Distribution coefficients of Cd, Co, Ni and Zn in Soils. *J. Soil Sci.* **39** 15-22.

BERN-LIEBEFELD HH (1991) Heavy metals in sewage sludge and town waste compost. In: Merian E (ed.) *Metals and their Compounds in the Environment.* VCH, Weinheim. 357-365.

BRUCE AM, COLIN F and NEWMAN PJ (1989) *Treatment of Sewage Sludge: Thermophilic Aerobic Digestion and Processing Requirements for Land Filling.* Elsevier Applied Science Publishers Ltd., North Ireland. 48 pp.

CECIL LH, DAVID RZ. and RICHARD K (1992) *Municipal Sewage Sludge Management Processing, Utilization and Disposal.* Vol. 4. A Technomic Publishing Company Book, USA. **72** 95-96.

CHANEY RL (1974) Crop and food chain effects of toxic elements in sludges and effluents. *Proc. Joint Conf. on Recycling Municipal Sludges and Effluents on Land.* July 9-13, 1973, Champaign, Illinois. Washington, DC: National Association of State Universities and Land Grant Colleges.

CONOR R (1980) *Metal Contamination of Food.* Applied Science Publishers Ltd., London. 20-205.

DU PLESSIS J (2004) Eutrophication management: new hope for troubled waters: The Hartbeespoort Dam test case. *The Water Wheel* **3** 16-19.

DU PREEZ LA, VAN DER MERWE W and TERBLANCHE JS (1999) Biosolids management at 18 wastewater treatment plants in South Africa - optimisation strategies. *Proc. Specialized Conference on Disposal and Utilization of Sewage Sludge: Treatment Methods and Application Modalities.* Athens, Greece. 13-15 October.

ELIOT E (2003) *Land Application of Sewage Sludge and Biosolids.* Lewis Publishers, U.S.A. 188 pp.

ENVIRONMENTAL PROTECTION AGENCY (EPA) (1993) *Federal Register, Part 2.40 CFR Part 257, Standards for the Use of and? Disposal of Sewage Sludge. Final Rules.* USEPA, Washington. **58** (32).

GARDINER WP (1997) *Statistical Analysis Methods for Chemists: A Software-Based Approach.* The Royal Society of Chemistry, Cambridge. 258-261.

GEORGE T and FRANKLIN LB (1995) *Wastewater Engineering: Treatment Disposal and Reuse* (Edn. 3). Tata McGraw-Hill Publishing Company Limited. New Delhi. 302-303.

HOU X and JONES BT (2000) Inductively coupled plasma optical/emission spectrometry. In: Meyer RA (ed.) *Encyclopedia of Analytical Chemistry: Applications, Theory and Instrumentation.* Vol. 11 Wiley. 9468-9483.

KNOX AS, SEAMAN JC, MENCH MJ and VANGRONSVELD J (2001) Remediation of metal and radionuclides contaminated soils by in situ stabilization techniques. In: Iskandar IK (ed.) *Environmental Restoration of Metals-Contaminated Soils.* CRC Press LLC, USA. 21-53.

KORENTAJER L (1991) A review of the agricultural use of sewage sludge: Benefits and potential hazards. *Water SA* **17** (3) 189-196.

METHOD 3050B (1996) Acid Digestion of Sediments, Sludges and Soils. Available on the Internet: http://www.epa.gov/epaoswer/hazwaste/test/pdfs/3050b.pdf. Accessed on 16 June 2003.

NHAPI I and TIRIVAROMBO S (2004) Sewage discharge and nutrient levels in Marimba River, Zimbabwe. *Water SA* **30** (1) 107-112.

ROY MH (1996) *Pollution: Causes, Effects and Control* (3rd edn.) The Royal Society of Chemistry, London. 71.

RUDD T (1987) Scope of the problem. In: John NL (ed.) *Heavy Metals in Wastewater and Sludge Treatment Processes: Sources, Analysis and Legislation.* Vol 2. CRC Press, Boca Raton. 2-23.

SCHMIDT JP (1997) Understanding phytotoxicity threshold for trace elements in land Applied sewage sludge. *J. Environ. Qual.* **26** 4-10.

SIMS JT, IGO E and SKEANS (1991) Comparison of routine soil tests and epa method 3050 as extractants for heavy metals in Delaware soils. *Commun. Soil Sci. Plant Anal.* **22** (11&12) 1031-1045.

SMITH R and VASILOUDIS H (1989) Inorganic Chemical Characterization of South African Municipal Sewage Sludge. Progress Report No. 4. DWT Contract Project No. 670/3122/9. WRC. Pretoria. 5-60.

SMITH SR (1996) *Agricultural Recycling of Sewage Sludge and the Environment.* Biddles Ltd. Guildford. 207 pp.

SNYMAN HG, TERBLANCHE JS and VAN DER WESTHUIZEN JLI (1999) Management of land disposal and agricultural reuse of sewage sludge within the framework of the current south african guidelines. *Proc. Specialized Conf. on Disposal and Utilization of Sewage Sludge: Treatment Methods and Application Modalities.* Athens, Greece. 13-15 October.

STEPHENSON T (1987) Sources of heavy metals. In: John NL (ed.) *Heavy Metals in Wastewater and Sludge Treatment Processes: Sources, Analysis and Legislation.* Vol 2. CRC Press. Boca Raton. 32-59.

SULTAN A and RAHMAN SM R (2001) Trace metals in soil-plant systems under tropical environment. In: Iskandar IK (ed.) *Environ-*

mental Restoration of Metals-Contaminated Solis. CRC Press LLC. USA. 230-240.

TCHOBANOGLOUS G and BURTON FL (1995) *Wastewater Engineering: Treatment Disposal and Reuse* (3rd edn.) Tata McGraw-Hill Publishing Company Limited, New Delhi. 88 pp.

TREWAVAS AJ (1986) *Molecular and Cellular Aspects of Calcium in Plant Development*. Plenum Press. USA. P1.

WEBBER MD, KLOKE A and TJELL JC (1983) A review of current guidelines for the control of contamination problems by metals in soils. Presented at the *3rd Int. Symp. of Processing and Use of Sewage Sludge*. Brighton. England. September. 27-30.

WERNER M (1980) Zinc tolerance by plants. In: Nriagu JO (ed.) *Zinc in the Environment, Part II: Health Effects*. USA. 415-432.

WRC (1997) Permissible Utilization and Disposal of Sewage Sludge (Edn. 1) Pretoria, South Africa. WRC Report No TT 85/97.

WRC (2002) Addendum to the Guideline on Permissible Utilization and Disposal of Sewage Sludge (Edn. 1) Pretoria, South Africa. WRC Report No TT 154/01.