EXECUTIVE SUMMARY

This research project forms part of a research program funded by the Water Research Commission that started in 2001 to critically assess the South African sludge legislation and revise the guidelines if necessary. This multidisciplinary research program includes the following projects:

- **WRC Project Number 1209:** An evaluation of dedicated land disposal practices for sewage sludge
- **WRC Project Number 1210:** Laboratory and field scale evaluation of agricultural use of sewage sludge
- **WRC Project Number 1240:** A technical and financial review of sludge treatment technologies
- **WRC Project Number 1283:** A metal content survey of South African sewage sludge and an evaluation of analytical methods for their determination in sludge
- **WRC Project Number 1339:** Survey and methodology for analyzing organic pollutants in South African sewage sludge

The results of the research projects will form the knowledge base to start a participative process in 2003 to develop Edition 2 of the Permissible utilization and disposal of sewage sludge guidelines.

The main aim of this study was to determine the current and future impact of DLD practices on the environment. The outcome of the study can serve as input for the revision of the guidelines for sludge disposal. The objectives of the study were as follows:

1. To evaluate the extent of the current practice of disposing of sewage sludge on dedicated land.
2. To evaluate the potential pollution risk this practice poses to the water environment at selected sites.
3. To estimate the future impact of dedicated land disposal of sewage sludge on the water environment.

Most of the wastewater treatment facilities in South Africa dispose of their sewage sludge on dedicated land disposal (DLD) sites (sacrificial lands), since this is the quickest and cheapest way to get rid of the waste. The sludge is regularly applied at high rates to the surface soils. No crops are grown and the land is only used for the disposal of sewage sludge. The impact of this practice on the environment is believed to be negative, but very little research has been done to determine the extent of the damage to the soil and water resources. Negative impact can be caused by erosion and run-off after rainstorms that will cause surface water pollution. The groundwater may also be contaminated due to the movement of heavy metals and nitrogen through the soil. It should also be determined whether the same set of guidelines for the maximum permissible levels of heavy metals in soils should be used for DLD areas as for agricultural land.

A survey in conjunction with WRC project number 1283 was executed to determine to what extent sacrificial land disposal is currently used in SA. The selection of the sites included sites from all the major cities, as well as smaller towns with and without industries. Questionnaires were used to determine amounts of sludge, application methods, time intervals between applications and other important information. Topsoil samples were collected at each site and analysed. The analyses included a semi-quantitative analysis (scan) of the total metal content (EPA 1050 digestion) of the soil sample to estimate the heavy metal concentrations, as well as analyses for essential plant nutrition elements (K, Ca, Mg and Na; total N; Total P), pH (H_2O), organic carbon content and particle size distribution (7 fractions).

The extent of dedicated land disposal (DLD) practices in South Africa is widespread. Stockpiling is the practice used by most of the sewage treatment facilities (40%), either as the only disposal method or a means to store the dried sludge until it is utilized by farmers and municipalities, disposed of in landfills or composted. Liquid sludge is applied to soils by 40% of the remaining disposal sites. This includes practices like irrigation, flooding, sludge ponds, instant lawn irrigation and paddies.

Thirty percent of the DLD sites were on sandy soils (<10% clay) with a high leaching potential while only 11% were on sandy clay and clay soils (>35% clay) where the adsorption capacity of the soils may impede groundwater pollution. The majority of topsoil samples had above average macronutrient and organic carbon contents, and 65% of the samples had pH(H_2O) values <6.5. Groundwater pollution at these sites with the low pH values is a possibility because many heavy metals are mobile under acid conditions.

The heavy metal analyses indicated that 88% of the topsoil samples had at least one element that exceeded the maximum permissible level (MPL) for soils that are used beneficially (Dept. Nat. Health & Pop. Dev., 1991). Nickel is the main element that was too high in most of the samples, followed by Zn and Pb. Other elements that were present in high concentrations were Cd, Cr and Cu.

It should be kept in mind that the MPL for heavy metals in soils was set for the beneficial use of sewage sludge for agricultural purposes and not for DLD practices. A separate set of guidelines should be considered for DLD practices after the completion of this study.

From the information collected during the initial survey, 40 sites were selected for further detailed studies. These sites included sewage works with different soil properties, application techniques, metal concentrations and period of sludge application. Soil samples were collected at three different locations and at five depths (to determine the mobility of metals and other elements) at each of the selected wastewater treatment facilities. Water samples were collected from boreholes where possible and analysed for the same elements as the soil. Four extraction methods were used to determine the metal content of the soil samples, *aqua regia* and EPA 3050 digestion (total), NH_4EDTA extractions (potentially bio-available fraction) and NH_4NO_3 extractions (soil solution fraction). The samples were analysed according to the information collected during the survey.

The selection of sites for the detailed study consisted of 14 sites with wet sludge application without beneficial use, 5 sites with sludge irrigation onto instant lawn (beneficial use) and 21 sites with dry sludge application (stockpile and belt press dewatered sludge). Seven of the sampled sites receive only domestic wastewater.

The total P content of 23 sites was above the average for normal soil (0.1%; Brady, 1984). None of the soil samples had above average total N (>1.5%; Sparks, 1996) even in the top 100mm of the soil profile. However, the analysis data of the groundwater samples had high NO_3 concentrations, which indicates leaching of nitrate. Sixty percent of the sampled sites had organic carbon contents higher than 1.2%, due to high organic matter application.

Correlations for all analytical methods were done for all the samples, only topsoil samples and subsoil samples (lowest soil layer sampled) to determine where the strongest correlation would be. The correlations indicated that the EPA 3050 and *aqua regia* methods could be used interchangeably for all the metals, except Ni, because of the were very strong (r^2 >0.82) correlations. The correlation between the NH_4EDTA and NH_4NO_3 extraction methods were strong for Cr, Ni and Cd. For Zn, Cd and Pb the correlation between the total methods (EPA 3050 and *aqua regia*) and NH_4EDTA were also strong.

Of the 40 selected sites, 35 sites had at least one heavy metal that exceeded the MPL for South African soils (Dept. Nat. Health & Pop. Dev., 1991). The total topsoil concentration of Cr was above the MPL for South African soils (80 mg kg^{-1}) in 50-53% of the sampled sites, followed by Ni (45-48% > 50 mg kg^{-1}), Zn (40-45% > 185 mg kg^{-1}), Pb (35-38% > 56 mg kg^{-1}), Cu (30-35% > 100 mg kg^{-1}), Co (25-33% > 20 mg kg^{-1}) and Cd (25-30% > 2 mg kg^{-1}). The percentage samples exceeding the MPL for South African soils (Nat. Dept. Health & Pop. Dev., 1991) decreased in the lower soil layers indicating accumulation in the surface layers due to surface application of sludge.

The high total metal concentrations in many of the soils, especially those that receive only domestic wastewater, may be due to high background concentrations of these elements in South African soils (Herselman & Steyn, 2001) and not only sludge application. Detailed studies of these sites, including surrounding areas to determine the baseline concentration of the area, is advised.

The NH_4EDTA extractable metal fraction gives an indication of the potentially bio-available or medium term risk of metals entering the environment. None of the sites (all soil layers) had NH_4EDTA extractable Cr and Pb concentrations above the NH_4EDTA threshold values. The potentially available topsoil Cd, Zn, Co, Cu and Ni concentrations in respectively 20% (Cd, Zn), 13% (Co, Cu) and 10% (Ni) of the sites exceeded the NH_4EDTA threshold values (Bruemmer & van der Merwe, 1989). There is thus a small medium term risk for environmental pollution.

The exchangeble (NH_4NO_3 extractable) Ni, Zn and Cd concentrations are reason for concern because 23-45% of the sites had concentrations above the NH_4NO_3 guidelines set for groundwater protection (Baden-Wurttemberg, 1993) in the topsoil and 23-25% sites had elevated concentrations of these metals in the 400-500mm soil layer, indicating a short term risk for groundwater pollution.

The lack of groundwater monitoring at most of the wastewater treatment facilities should be addressed. Seven of the 9 groundwater samples that could be obtained showed high NO_3 concentrations (>6 mg l^{-1}). This would probably be the case at most of the treatment facilities. The organic C in the top 200mm of the soil profile may adsorb some nitrogen, but the rest is mobile and leach through the soil. Therefore, the soil analyses do not show high total N concentrations. In some cases, where NH_4NO_3 extractable metal concentrations in the 300-500mm soil layers are high, groundwater pollution by heavy metals may even be possible, especially if the soil has low clay content.

Some degree of leaching of the heavy metals occurred at some of the sampling sites and the average depth of leaching was 100-200mm. Deeper than 300mm the metal concentrations in most soil samples reached background concentrations. The elements that leached in most soils were Co and Ni. The leaching of the metals, in spite of the high organic carbon content of the soils, was due to the extremely low soil pH(H_2O) of most sites.

Statistics of the data indicate no significant differences between sludge type (wet or dry) and leaching, or age of the disposal sites and leaching. It should be kept in mind that most of the sampled sites receive industrial effluent, therefore the metal loading of the sludge at these sites is probably very high. Taking into account the age of the disposal sites, the frequency of sludge application and the metal load of the sludge, the depth of leaching is surprisingly shallow in most soils, in spite of the low soil pH(H_2O) and clay content.

There is a need to be able to predict the impacts of the practice of amending soils with sewage sludge on aquifers. The current investigation explores the feasibility and utility of chemical fate and transport modelling as a means of predicting the mobility of metals inherent in sludge-soil mixtures, under a number of specific environmental conditions.

A very extensive literature survey revealed that many famous scientists have attempted the task of modelling the migration of metals in sludge-amended soils. To date, no satisfactory predictive model has been developed. Published experimental data is in conflict with respect to relative strengths of binding of metal ions to sludge-soil matrices, and with respect to potential mobility of the metals in the environment. Not only are sludge and soils highly site-specific in their chemical nature, but so is the nature of biota (species and community structures) responsible for degrading organic material in the sludge/soil mixtures into potentially metal-binding soluble material. Despite the difficulties, some headway has been made in determination of metal binding constants by thermodynamic means.

A chemical model was constructed using PhreeqC, a geochemical fate and transport modelling package extensively used in the groundwater field. The model was constructed from published thermodynamic data, and calibrated against simple conceptual models of the behavior of soils, and natural organic matter. A subset of the field results from this study was analysed statistically to determine a Reference Behavior Pattern to benchmark the model against. The model was further calibrated against the extractions of metals from the sludge/soil samples by NH_4NO_3 and NH_4EDTA.

Literature and modelling studies indicated that the organic carbon component of the sludge/soil matrix is principally responsible for the fate of metals. Scenarios were modelled, using cadmium as a representative metal ion. The scenarios are presented below with the results of the simulations:

- Elution with dilute saline solution at pH 7 - metals were not mobilized
- Elution with dilute saline solution at pH 6.5 - metals were not mobilized
- Elution with dilute saline solution at pH 5.0 - metals were completely mobilized
- Effect of maintaining carbon content of sludge layer - microbial decomposition of organic carbon will continuously produce soluble organic matter, which will bind metals and mobilize the metals
- Effect of maintaining high pH through liming - addition of lime involves the addition of calcium ion which out-competes toxic metal adsorption to sludge/soil matrix, resulting in substantial mobilization of metals

- Effect of cessation of sludge addition - metals would be mobilized in the short term, due to continuous production of soluble, metal-binding organic matter, but will cease in the long-term. Literature suggests that after ten years, metals will cease to be mobile

In general only a few of the disposal sites have sound management practices in place. Most of the disposal sites are not fenced off and are very close to populated areas. General access by the public occurs and in some cases the local people harvest edible plants that grow on the disposal sites.

The majority of the disposal sites are on even terrain, but most of those that are on a slope have no erosion control measures in place even though they are near surface water bodies. Surface water monitoring at these sties is recommended.

Generally the larger cities and metropolitan councils were found to be knowledgeable in sludge management and legislative requirements but this was not the case in other towns. Many plant managers didn't really care where they put the sludge, as long as it is disposed of. No systems exist at most wastewater treatment facilities to manage the disposal of the sludge. At two wastewater treatment facilities raw sewage was disposed of on the disposal site.

The following recommendations should be considered:

- Clear demarcation of sludge disposal areas with restrictive access
- Continuous groundwater and surface water monitoring should be enforced
- Erosion control measures where necessary
- Sound management practices at the disposal site to regulate disposal
- Prerequisites for permit – no disposal on sandy soils, safe distance from water bodies etc.
- Nitrogen should be considered in the guideline for sludge disposal because it poses a bigger threat than the metals
- Guidelines should be set for DLD specifically