LAND-BASED EFFLUENT DISPOSAL AND USE: DEVELOPMENT OF GUIDELINES AND EXPERT-SYSTEMS-BASED DECISION SUPPORT

K. O'H. MURPHY

Report to the
WATER RESEARCH COMMISSION
by the
CAPE WATER PROGRAMME
DIVISION OF WATER, FORESTRY AND ENVIRONMENTAL TECHNOLOGY
CSIR, STELLENBOSCH

WRC Report No. TT 125/00

CSIR Project No: **ENV/S-C 99015**

Obtainable from:

Water Research Commission
PO Box 824
Pretoria
0001

The publication of this report emanates from a project entitled:
Land-Based Effluent Disposal and Use: Development of Guidelines and Expert-Systems-Based Decision Support (WRC Project No. K5/698).

DISCLAIMER
This report has been reviewed by the Water Research Commission (WRC) and approved for publication. Approval does not signify that the contents reflect the views and policies of the WRC, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

NOTES ON THE DISTRIBUTION OF THE SOFTWARE AND USER'S GUIDE
The expert systems-based software, ELADS (Effluent to Land Decision-Support software), may be down-loaded from the WRC internet site: http://www.wrc.org.za/ Responsibility for decisions made using ELADS rests with the user.

CURRENT STATUS AND FURTHER CHANGES
Please note that the current version of ELADS is a simple working version which has not been completely validated. It should therefore be considered useful for demonstration purposes only.

CONTENTS

LIST OF TABLES, FIGURE AND TERMINOLOGY

Table **Page**

Term	**Description applicable to this report**
Alkalinity	The capacity of water to neutralize acids (as calcium carbonate concentration in mg/ℓ).
BOD	Biological oxidation demand: Quantity of oxygen used in the biological oxidation of organic matter for a specific time: A measure of short-term biodegradability.
CEC	Cation exchange capacity: A measure of the sum of exchangeable cations that a unit mass of soil can adsorb.
COD	Chemical oxidation demand: Quantity of oxygen used in the chemical oxidation of organic matter: A measure of long-term biodegradability.
Effluent	Wastewater flowing from an industrial process or a treatment plant.
Permeability	The ease with which gas or liquids pass through a soil or soil horizon.
pH	Degree of acidity/alkalinity. Low pH: acidic, high pH: alkaline.
SAR	Sodium adsorption ratio. SAR = Na / (Ca+Mg)/2)^0,5
TDS	Total dissolved solids: The total mass of dissolved salts in a litre of water. A measure of salinity.
Toxic substance	An element or chemical compound which has the potential to cause sickness or death when taken up by plants or animals in relatively small quantities.
Leaching factor (LF)	The proportion of total moisture applied to the land surface, which percolates through the soil until it is out of reach of plant roots and where capillary forces cannot bring the moisture back to the surface.
Crop factor (CF)	The ratio of potential evapotranspiration of the crop and ground surface to potential evaporation from an equivalent area of open water.

More comprehensive terminology descriptors can be found in Department of Water Affairs and Forestry (1996).

EXECUTIVE SUMMARY

Background and motivation

South Africa faces major problems in disposing of its liquid and solid wastes in an environmentally sustainable manner, as its waste production is exponentially increasing and costs are also increasing per unit mass of waste to be disposed of in an environmentally sustainable way. Being a semi-arid country, South Africa is facing a further problem regarding severe limits on available, good-quality water resources.

Hence the major problems are:

(i) The ever-increasing waste-production volumes with increasing costs of treatment and disposal, present significant implications for our economy.

(ii) Water is a scarce resource. As demand outstrips supply, this forces up the cost of water and imposes more severe restrictions on water use.

(iii) Water pollution has become an ever-increasing threat to our economy, quality of life and environment.

It is believed that South Africa needs to utilize effluents in such a way that wastewater is used for non-potable purposes (such as for agriculture) in place of fresh water, and that the latter water is reserved for potable and recreational use. As effluent producers are likely to want to reduce effluent volumes needing to be disposed of by evaporating as much of it as possible, a regulatory mechanism is needed to ensure that excessive amounts of moisture from effluent are not irretrievably lost to the atmosphere. It is important that crops and soil be selected primarily on their capacity to treat non-saline effluents effectively, and that effluent then be applied at a rate not greater than that which matches this capacity. Land application of effluents needs wise management and control in order to:

❑ minimize health risk to field workers and crop consumers,

❑ minimize pollution risk to water resources,

❑ minimize needless water losses to the atmosphere,

❑ minimize the impact on the environment (e.g. ecological impact; odour impact),

❑ maximize the benefits in terms of crops grown,

❑ save on effluent treatment costs, and

❑ maximize the availability of higher quality source water for alternative use, etc.

The Water Acts of 1956 and 1998 require large industrial users of water in South Africa to return water to the point (or catchment) from which it is abstracted, in a condition suitable for reuse by downstream users. Regulations in terms of the Health Act of 1977 lay down rules regarding whether the land-application of sewage effluent for specific uses is allowed or not (Department of National Health and Population Development, 1978). The Environmental Conservation Act of 1989 recommends that waste be reduced at source or else recycled in preference to being disposed of. Effluent consists of a combination of water and waste, and in order for effluent disposal to comply with these acts, the following is believed to be relevant:

Where it is not feasible to treat an effluent to the standard required for return to the point of abstraction of the original fresh water, other options should be promoted, such as the reuse of the effluent with or without pretreatment (dependent on characteristics of the effluent). If the effluent is pathogenic, the health regulations (Department of National Health and Population Development, 1978) may be employed to help determine what reuse options are acceptable for the effluent in question. Reuse of effluents may be for industrial or agricultural purposes. In the case of the latter, organic and nutrient contaminants as well as the moisture in effluent can be beneficially utilized for growing crops and grasses. The organic content, if high enough, helps to improve soil structure and also performs as a slow-release fertilizer, and the nutrients help supply immediate plant nutrient needs. Thus the reuse of such effluents results in a saving on fertilizers. The moisture in effluent may be used in place of irrigating with fresh water: “By utilising moisture in effluent, fresh water which would normally be required for agriculture may be saved for other use.” (Shuval et al., 1986). Regarding the application of effluents to land for beneficial purposes in South Africa, there is believed to be a need for developing further guidelines and modifying the existing ones, so that together they may underpin (or form part of) an environmentally compatible effluent management strategy for South Africa, compatible with the latest government policies relating to water, health, environmental conservation, agriculture, forestry and land-use (examples of relevant legislation follow):

Constitution of the Republic of South Africa (Act No 108 of 1996)
Physical Planning Act, No 125 of 1991
Environment Conservation Act, No 73 of 1989
National Environmental Management Act, No 107 of 1998
Health Act, No 63 of 1977
Atmospheric Pollution Prevention Act, No 45 of 1965
Land Use Planning Ordinance, No 15 of 1985
Nuisance Regulations137/1974
Environmental Health By-Law 314/1990
Draft White Paper on Environmental Management Policy for South Africa, 1998
Draft White Paper on Integrated Pollution and Waste Management for South Africa, 1998

In the light of increasing environmental consciousness, and due to the rapidly expanding populations in South Africa, there is a large increase in the production of liquid and solid wastes together with diminishing options for environmentally-sustainable disposal of that waste. Land application for treatment of sewage and other organic and pathogenic effluents should enjoy high priority in South Africa, as research shows that soils are amongst the most efficient means of treating such effluents (Bouwer, 1985). Although this may be considered a cheap option, it must be considered together with suitable site selection as well as proper design and regular upkeep of primary treatment facilities and land application systems. Where soil treatment facilities are installed and overseen by a responsible authority and no important water resources are at risk, it is believed that land-application systems should find widespread use for low population density areas in South Africa.

Conventional wastewater treatment systems (such as activated sludge systems) are not able to remove all the nutrients or pathogens in wastewater that soil and vegetation can (Bouwer, 1985; Shuval et al., 1986). By utilising nitrogen and other nutrients in percolating effluent, managed crops help cleanse the effluent from wastewater treatment systems of nutrients and in so doing, save on the cost of specialized effluent treatment and on the cost of fertilizers. Prior to discharge to a river or stream, treated effluent usually needs to be chlorinated in order to kill off any existing pathogens in the effluent. Chlorination of treated effluent from a conventional treatment system forms tri-halomethanes (THMs) which are known to present a risk to in-stream ecosystems and, to a lesser extent, a cancer risk when used for drinking water purposes (Khouri et al., 1994). Given the constraints of proper site selection, system design and effluent management, treatment of partially-treated effluent by soils is believed to be an effective, low-cost, environmentally friendly alternative to full conventional treatment.

There are several options to consider when applying effluent to land: to **supply crop nutrient** requirements; to **supply crop water** requirements or to **treat the effluent** by employing the filtering capabilities and chemical attenuation characteristics of soil and vegetation. A further option, **disposal of effluent** to land, should preferably be the last option made available to effluent producers, and where practised, it needs to be done without an unacceptable negative impact occurring on human health, water resources or the environment. In most countries, the major objective of effluent to land applications is the disposal of effluent at minimal cost/impact to (a) the effluent generator, (b) human health and (c) the receiving environment (Shuval et al., 1986; WHO, 1995). Guidelines are needed to help address the issues of crop nutrient and water requirements, on-land effluent treatment options and the impact of effluent application to land on human health and on the receiving environment.

The need for guidelines for effluent application to land is becoming more acute, and as these guidelines are necessarily complex, there is a need for such guidelines to be incorporated in user-friendly software. Software which supplies tools to help in guideline interpretation and implementation, if this is integrated with some form of routine "intelligence", should be of value to potential users, as such users are not likely to have all the expertise needed in order to interpret and implement the guidelines. The development of expert systems-based decision-support tools is believed to be a way to obtaining such software.

Objectives of the study

The overall objective of the research project is to develop expert systems incorporating guidelines and advice on land-based effluent disposal and effluent use, together with relevant decision-making processes, in order to provide decision-makers with appropriate, readily accessible information and expertise on personal computers.

Aims:

a. Develop an expert system to give advice and to present regulatory conditions for effluent disposal-to-land permitting purposes.

b. Develop an expert system whose purpose is to present relevant guidelines and to give advice on the beneficial use of effluent for agriculture and forestry.

c. Identify a suitable IEM strategy for effluent-disposal or effluent use permitting purposes, and determine how this strategy may be used to underpin the permitting process. Develop a coordinating expert system whose functions are to give advice on the permitting strategy, to give other supporting information and to call up the other expert systems.

d. Develop an expert system to help select cost-effective sewage treatment and effluent to land disposal facilities for communal purposes (e.g. schools, day-care centres, clinics, shopping areas) in rural developing communities.

Results

Although the objective and aims were to develop expert systems, before the software could be developed there was a need first to gather relevant information applicable to South African conditions. It was found that there is insufficient literature available applicable locally, and so a search was made for relevant guidelines from overseas literature, and several overseas experts were visited in order to gather practical information and further literature. There is a wealth of literature on the irrigation of partially-treated sewage effluents to land in terms of impact of pathogens on human health, in terms of the impact of salts on plant health and soil permeability, and on moisture and nutrient requirements of crops. There is some information available on the impact of trace elements which is relevant for sludge, and very little which is relevant for effluents. The World Health Organization (WHO, 1995) produced a report which recommends that a procedure similar to that which is used in the United States for the land application of sewage sludge (which is also similar to the one currently used in South Africa), be used for effluents. However, it is believed that priority contaminants for sewage sludge are mostly different from those for effluent, and a specific problem relating to the bioavailability and mobility of contaminants in soil would depend not only on the contaminant itself, but also on the form of contaminant. Contaminants in sludges are likely to be mainly in their insoluble form, whereas contaminants in effluents are likely to be mostly in their soluble form. For similar concentration levels, the impact on plants and on groundwater of contaminants in effluent is therefore likely to be higher than for contaminants in sewage sludge, and so a risk-based special study is recommended for priority contaminants in land-applied effluent.

An attempt has been made in this study to characterize effluent and soils in order to facilitate the planning and management of effluent application to land. The effluent characterization needs to account for the potential risk that contaminants in effluent might have on plants, animals and water resources. The soils characterization needs to be able to describe the potential ability of soils to attenuate contaminants in effluent, given a few key soil characteristics.

A procedure to address the suitability of effluent for irrigation has been drawn up. The framework adopted for this is similar in many respects to the one used for the permitting procedure for sludge application to land in South Africa (WRC, 1997). This was done as it will be more likely to be adopted for permitting purposes than the more complex one drawn up to follow an environmental screening approach (See **Figure 1** in the appendix). The first stage addresses an effluent treatment stage/land-use screening procedure (like the one currently used for effluent application to land in this country (Department of National Health and Population Development, 1978)), the next stage addresses suitability of site conditions, and the third addresses sustainable land application rates and also specifies applicable design, planning and management measures. The procedure assesses the suitability of an effluent for application to land, dependent on:

(a) effluent pathogen characteristics/treatment stage and application/crop type, in accordance with health guidelines (for example: Department of National Health and Population Development, 1978);

(b) the required site-specific characteristics on which to base a judgement in terms of acceptable slope, depth-to-groundwater, distance to residences, geology and soil characteristics (amongst others);

(c) acceptable application rates dependent on crop nutrient requirements, contaminant loading rates and climatic water balance limitations;

specifying applicable design, planning and management measures. The suggested procedure is presented in more detail as follows:

Effluent / crop type / land-use acceptability criteria:

Identify relevant effluent/ crop type and effluent/ land-use characteristics. Determine if the combination is acceptable or not in terms of health guidelines. If acceptable, indicate what restrictions or protective measures (if any) are required. Unacceptable combinations represent overriding criteria.

Effluent/crop, climate and site criteria: Identification of further overriding criteria, limiting conditions and relevant corrective measures:

(i) Information gathering

- ❑ Obtain effluent analysis and soils analysis data.
- ❑ Obtain relevant information on topography and climate.
- ❑ Identify key/ important criteria on geology, geohydrology and hydrology.
- ❑ Identify other important site criteria, e.g. adjacent land-uses, land-zoning, site access, etc., and measure relevant separation distances.
- ❑ Identify suitable crops or else select and assess the crop types that have been specified by site owner/manager.

- ❑ Obtain seasonal crop factors and nutrient requirements of the relevant crop(s), taking into account crop growth characteristics and expected nutrient removal at harvest.

- ❑ Obtain data on effluent application area(s) and monthly volumetric effluent discharges.

(ii) Derivation of results

- ❑ Derive monthly climatic "water balance" criteria, taking into account leaching and crop factors.

- ❑ For soil, derive current (bioavailable) toxic contaminant levels and also residual N in soil.

- ❑ Derive nutrient, organic, contaminant and moisture application rates.

- ❑ Determine if any limits have been overstepped in terms of nutrient, contaminant and moisture application rates, and if so, by how much.

- ❑ If any limiting condition is overstepped, determine percentage reduction requirements on effluent in order to satisfy each of the limiting conditions.

- ❑ Present options on how to address relevant limiting conditions.

- ❑ Allow changes to be made to effluent application rates and crops to be grown.

- ❑ Re-assess to what extent any potential limiting conditions may be overstepped, then allow further changes and reassessments to be made until a suitable application rate and crop type are found.

- ❑ Consider any mitigatory measures that may be applicable, and recommend those that are most suitable, if the required effluent application rates are to be allowed.

(iii) Reporting requirements: Identify overriding and other important issues and link each to relevant regulatory conditions as well as mitigatory measures, where applicable, and attach relevant recommendations and/or other advice.

- ❑ Indicate whether the effluent type /land-use and effluent type/ crop type combination is acceptable.

- ❑ Taking into account the type of ownership/control over site, do the following:

  - ➪ Indicate whether the required effluent volume application patterns, etc. are acceptable.

  - ➪ Indicate whether effluent/soils analysis results and important site criteria are acceptable.

- ➪ Highlight potential problems relating to other site criteria.

- ➪ If the proposed effluent application to land is acceptable, list relevant planning/design/management measures.

- ➪ If the proposed effluent application to land is not acceptable in its current form, indicate why not, and list what conditions, if any, could be required for the proposal to be reviewed.

This procedure is complex, and the software developed as part of this project is designed to provide decision-support tools for permitting officials and others who are involved in tasks relating to effluent irrigation to land for long-term sustainability. The original aim here was to develop expert systems-based programs, and during the course of the study it became evident that, for some components, procedural and database programs would be more effective for some computations (and these have been utilized for such purposes), and expert systems extensions can then be used to interpret the results.

Before being in a position to develop software, it is necessary to have guidelines. There being no guidelines for general application of effluent to land other than Thompson's guidelines (Thompson, 1985) and the Department of Health’s screening regulations, it was decided to use these as a basis for software development. However, it became evident that these guidelines were limited in terms of the effluent categories presented in them, and so an effluent characterization investigation was done as part of the study. It is believed that effluents need to be suitably characterized in order to facilitate guideline development. The following is a summary of the most important guidelines relating to effluents which display certain characteristics:

- ❏ Effluents with a high pathogen content require certain treatment stages and controls on crop irrigation practices to be specified (backed up by monitoring), with the aim of protecting human health.

- ❏ Effluents with significant quantities of potentially toxic trace elements need to be restricted in terms of levels of contaminant build-up in site soils as well as in terms of annual application rates. This is neccessary to protect human, animal and plant health via different food-chain pathways.

- ❏ Effluents with high nutrient loadings need to be restricted in terms of the amount that can be applied to land in terms of what crops need, and soil liming may be required to counteract the effects of soil acidification by organic and nitrogenous effluents.

- ❏ Effluents with significant concentrations of macro elements (e.g. TDS, Cl, B, Na) need to be applied to those crops and soils which are relatively insensitive to such concentrations, and sophisticated irrigation and soil management may need to be carried out to minimize the impact of those macro elements on crops and soils. (The impact on ground and surface waters from saline return flows is not addressed in this study.)

- ❏ Effluents with a high concentration of biodegradable organics ("high COD effluents") need to be applied to land with consideration for impacts in terms of pathogen growth, odour generation, insect breeding and soil acidification. Further, the likely effects of bacterial slime layers on reduced soil permeability and the impact of anoxic conditions in soil on plant root health may require that artificial drainage and wetting/drying cycles be instituted.

- ❏ Effluents which are acidic or alkaline, and those which contain high concentrations of suspended solids, detergents and grease generally need to be treated prior to land application. Acidic or alkaline effluents are likely to re-mobilize ionic contaminants sorped to soil particles. Effluents which contain high concentrations of suspended solids, or oils and greases, can clog soil pores at the soil surface, thus preventing irrigated effluent from percolating down into the soil, and also causing plant roots to suffocate from lack of oxygen. Detergents can remobilize contaminants in the soil, carrying them down to groundwater. High-sodium, low TDS effluents can also cause soil clogging in soils which have a significant clay content (Pettygrove and Asano, 1990).

- ❏ Soils need to be suitably characterized in order to help describe their potential ability to attenuate contaminants in effluent, given a few key soil characteristics. The following comments are relevant:

    The overriding factor which influences the mobility or bioavailability of ionic contaminants in soil is pH (Allen, 1997), where low pH mobilizes cationic contaminants and high pH mobilizes anionic contaminants in a soil solution. Secondary factors are the soil media type, where organic carbon, non-kaolinitic/kaolinitic clays, iron/ manganese oxides/oxy-hydroxides and carbonate soils are most effective in attenuating cationic contaminants in low and neutral pH conditions, and to a lesser extent in attenuating anionic contaminants in neutral to high pH conditions. Organic carbon is most effective in attenuating certain heavy metals and non-volatile organic chemicals.

    Effluents which contain high levels of pathogens, such as partially treated sewage effluents, are probably best applied on clay soils which contain humus and iron (e.g. dark red clayey soils).

    Sorption characteristics of viruses, which are the smallest most mobile pathogens in soil, are similar to those of anionic trace contaminants. Hence soils which have a high percentage of organic carbon, iron oxide and clay are considered suitable for virus sorption. Sorption of viruses by soil media therefore significantly reduces their bioavailability and their leachability. Larger pathogens are rapidly filtered out in clayey soils.

- ❏ The more mobile a contaminant is, the more it presents a risk in terms of groundwater contamination. On the other hand, the less mobile a contaminant is, the more the likelihood of build-up of contaminant concentrations in the soil surface to levels which could represent an unacceptable risk-factor to plants, animals and humans (for the latter two, this would be from eating plants or ingesting soil). However, the risk implied in the latter is usually small when considering agronomic applications.

ELADS (Effluent to Land-Application Decision-Support software) is the expert systems- based decision-support software developed as part of this project. It has been designed to address sewage effluents specifically, but could also be used for organic effluents, especially if organic effluents are considered to be pathogenic, and to some extent it can be utilized for nitrogenous effluents and for effluents containing potentially toxic trace elements. ELADS may be readily modified so that any site, soil or effluent-related limits specified by new regulations can be quickly implemented in the software. Although ELADS has been designed to produce meaningful results, it is limited in the extent of application (e.g. most components only address sewage effluents) and it has not been extensively tested (for example, it has not been tried out with proposed users).

Components of ELADS include:

- ❏ A health-permitting tool for sewage effluent (incorporates regulations promulgated in terms of the Health Act of 1977).
- ❏ A site-assessment advisor for sewage effluent, which may also have applicability for organic effluents (no South African regulations are incorporated).
- ❏ Soil contaminant limits assessment component (the South African limits applicable for sludge are incorporated, but should have no regulatory standing for effluent).
- ❏ Monthly precipitation-evaporation assessment tool.
- ❏ Effluent application rate assistant (no known South African regulations exist for this).
- ❏ Crop selection assistant for crops (addresses crop sensitivity to TDS, Cl and B - not a regulatory tool).
- ❏ Sewage effluent health risk versus cost comparative assessor (based on information from the London School of Hygiene and Tropical Medicine - may not be compatible with current South African regulations).
- ❏ Sewage treatment system option selection assistant (this is not a regulatory tool).

A prototype soils attenuation expert system has been developed as part of another project funded by the Water Research Commission (Sililo et al., 1999).

Recommendations

Land application of sewage and other organic/ pathogenic effluents for beneficial purposes should enjoy high priority in South Africa, as:

- ❏ research shows that soils are amongst the most effective means of treating such effluents;
- ❏ crop irrigation allows the nutrients in effluent to be recycled, thus reducing the need to add fertilizers to crops and, as a result of crops reducing nutrient concentrations in effluent, the potential impact of such nutrients on water resources is reduced;

- irrigation with effluents in place of higher quality source water frees the latter for alternative use.

Along with the above comes the need to ensure that proper mitigation measures are in place, that land application and drainage facilities are properly installed, that the sites are properly managed, and that the environmental impact of such activities has been assessed and accounted for. In order to carry out the above, not only are restrictions needed in terms of effluent type/ treatment stage and land-use category, but also restrictions in terms of effluent type/ treatment stage and the following:

- allowable site parameters (slope, depth to groundwater, etc.),

- suitable soil characteristics, and

- allowable maximum effluent application rates.

Together with the above comes the need for the development and institution of suitable procedures designed to:

- control the activities of effluent producers, and

- help effluent producers to manage their effluents in an environmentally sustainable yet affordable way.

These procedures are necessarily complex, so there is a need to have available suitable decision-support tools for both administrators and site managers. Software tools could be in the form of "intelligent advisors", geographic information systems, database systems, "web-based" communication tools and more. The expert systems-based software developed for this project, once modified, expanded and validated, should provide the required administrative advisory system. Suitable links from this software to GIS systems, databases and the Web could also be established. (There are active links to dBase tables in the current software.)

Further measures to help reduce the impact of effluents on groundwater include the following:

- Plant suitable crops in vulnerable areas:

  Maize, sugar cane, certain root crops and fruit trees can utilize nitrogen located as deep down as 2 metres. Unused nitrogen near the surface of the soil during the previous growing season will most likely still be located in the root zone the following year, and so not be lost to these plants (Burt and Haycock, 1993; Canter, 1997; Suarez, 1989).

  Deep-rooted plants with high water requirements, including most species of evergreen tree, help to lower the groundwater table and to keep salts suspended in the vadose zone. (Suarez, 1989). Of all vegetation types, woodlands normally have the lowest concentration of N in groundwater (Strebel et al., 1989).

- In arid areas, plant crops which require less water.

For brackish effluents, plant salt-resistant crops so that less effluent is required for leaching purposes (Department of Water Affairs and Forestry, 1993).

- ❑ Establish buffer-strips:

  Trees and shrubs growing in riparian (buffer) zones with shallow water tables reduce nitrogen in groundwater (Power and Scheepers, 1989). As discussed elsewhere, Eucalyptus trees are in many cases good candidates for this purpose.

- ❑ Use soil cation exchange capacity (CEC) to help define relevant application-rate limits for heavy metals.

  As most potentially-toxic inorganic contaminants are cationic, it is recommended that soils be tested for cation-exchange capacity prior to determining what contaminant application-rate limits are applicable. It is recommended that for heavy-metal contaminants and for soils with a CEC of less than 5 meq/100g, use conservative limits that are normally defined for non-calcareous sands. For soils with a CEC of between 5 and 15 meq/100g, use limits which are double the most conservative limits, or preferably use the following equation:

  $$\text{New limit} = (\text{most conservative limit}) * (\text{CEC} - 1)/4$$

  For soils with a CEC greater than 15, use limits which are four times greater than the most conservative limits (U.S. Environmental Protection Agency, 1992).

It is recommended that further research be carried out on the bioavailability and mobility of priority contaminants in effluent applied to land, with the aim of determining realistic limits in terms of contaminant mobility and distance to a water resource, soil attenuation, crop and animal uptake, the toxic nature of a contaminant, and limiting pathways, amongst others. The limits to be defined should relate to contaminant concentration in effluent, to concentration levels in irrigated soils and to annual land-application rates. Research efforts should be aimed at high-priority contaminants which are likely to be found in effluents such as treated sewage effluents and rural industrial effluents (the latter would be according to .

Presentation of papers at symposia or in journals is recommended for technology transfer purposes. Demonstration of software at workshops, as well as via WRC's website is recommended for educational and validation purposes.

Conclusions

The following aspects have been addressed in the report:

- ❑ Characterization of soils and effluents for crop-irrigation purposes.
- ❑ Suitable crop types, soil characteristics and design/planning/management aspects (in terms of effluent characteristics).
- ❑ Limiting parameters that affect the application rate of effluent in terms of major effluent constituents (excluding macro elements such as sodium and chloride ions).

- Given the objective: to dispose of as much effluent as possible over a limited land-area with minimal impact on the environment, the following aspects are considered:
  - i) crop nutrient requirements,
  - ii) crop water requirements,
  - iii) use of vegetation and soils to treat effluent to an acceptable standard.

- Management options which effectively reduce risk of contamination of water resources or else enable more effluent to be applied to a restricted land-area.

- Identification of suitable wastewater treatment system options given the importance of multiple decision criteria.

It is believed that the contract objectives have been achieved in all aspects except some which relate to the development of an IEM strategy:
"Identify a suitable IEM strategy for effluent disposal or effluent use permitting purposes, and determine how this strategy may be used to underpin the permitting process. Develop a coordinating expert system whose functions are to give advice on the permitting strategy, to give other supporting information and to call up the other expert systems."

A flow chart (see **Figure 1** in the appendix), depicting an effluent to land assessment procedure which could fall within an IEM strategy, has been drawn up. It is designed to follow environmental screening principles and to address potentially overriding conditions “up front” so that these may be identified early in an investigation. The procedure is considered to form only part of an IEM strategy. **Table 9** (see appendix) contains the task categories and details for the above procedure.

The coordinating expert system has not been developed so as to underpin the procedure. There are several reasons for the latter:

> Firstly, the procedure depicted in **Figure 1** is considered unlikely to be suitable for permitting purposes in South Africa, although it should be useful for an effluent-to-land suitability study (as part of an EIA), so an alternative procedure which is similar to the one used for sludge application to land in South Africa (Department of National Health and Population Development, 1978) was adopted for expert systems development purposes.
>
> Secondly, the coordinating expert system is designed to give the user freedom to access a component directly without having to first complete other components, as is implied in the adopted procedure.
>
> Thirdly, a help file system has been drawn up so that the user can access the adopted procedure and other supporting information in a separate text window alongside the "working" window. In this way, a new user is guided through the process, whereas an experienced user can take whatever route considered appropriate for the task at hand. The help file system also provides context-sensitive information for the task at hand.

ACKNOWLEDGEMENTS

The Steering Committee responsible for this project consisted of the following persons:

Mrs A P M Oelofse	Water Research Commission (Chairperson)
Dr I M Msibi	Water Research Commission
Dr G Offringa *	Water Research Commission (Chairperson)
Mr E O Jacobs	Department of Water Affairs and Forestry
Mr G McConkey	Department of Water Affairs and Forestry
Mr J L J van der Westhuizen	Department of Water Affairs and Forestry
Mr F J van Eeden	Resource Conservation, National Department of Agriculture
Mr B J van Niekerk	Department of Agriculture
Mr G M Arendse	Department of Environment Affairs and Tourism
Mr T L Ramaema *	Department of Health
Mr O Hempel	Water Research Commission (Committee Secretary)
Mr H J C Smith	Institute for Soil, Climate and Water
Dr G Tredoux	Cape Water Programme, Environmentek, CSIR
D van Nieuwenhuizen	Resource Conservation, National Department of Agriculture
Mr K O'H Murphy	Cape Water Programme, Environmentek, CSIR

* Attended at the beginning of the project.

Grateful acknowledgements go to the:
Water Research Commission for financial support of this project;
Research Managers, especially Mrs A P M Oelofse, for support and guidance of this project; and
Steering Committee members for their contributions.

The following persons are thanked for their special contributions and support.
Mr F J van Eeden
Mr G McConkey
Mr H J C Smith
Dr G Tredoux
Mr B J van Niekerk

Mr K Tucker of the Cape Water Programme, Environmentek, CSIR, is gratefully acknowledged for his efforts in developing components of the decision-support software and in developing the comprehensive help-file system.

DISCLAIMER

A DOS-based, prototype soil/vadose-zone attenuation expert system, which addresses the relative potential of soils to attenuate certain types of contaminant, given the results of chemical analyses of soil samples, has been addressed in **Chapter 7** of the WRC report entitled "Investigation of the Contaminant Attenuation Characteristics of the Soil Aquifer System with Special Emphasis on the Vadose Zone" (Sililo et al., 1999). The expert system does not address soil forms and families. However, the author believes it should be possible to estimate those chemical characteristics of a soil which are important for attenuation purposes given a soil's form and family, its colour, physical characteristics, topographical situation and origin (parent rock), as well as the vegetation cover and climatic factors at a site. If required, the expert system can be updated, validated and converted to "Windows" format.

In this report, the phrase "effluent disposal" relates to the discharge of effluent to land with no expressed purpose of treating or reusing the effluent.

The recommendations made in this report are not believed to conflict with the guidelines in the WRC report: "Guidelines for Catchment Management to Achieve Integrated Water Resources Management in South Africa" (Report No. KV 108/98). These recommendations also do not take into account any possible changes to the legislation as a result of the implementation of the National Water Act of 1998, or of possible changes in legislation as a result of the implementation of new acts such as the Agricultural Act and the Health Act. This report contains recommendations only, and should not be seen as having any regulatory authority.

This report does not attempt to address in detail the efficient use of effluent for irrigation purposes, the suitability of crops grown under South African conditions, or the suitability of soils in terms of any soil classification system used in South Africa. It also does not address the variable toxicity of elements whose toxicity depends upon their oxidation status.

1 INTRODUCTION

1.1 Effluent application to land

South Africa faces major problems in disposing of its wastes in an environmentally sustainable manner. In the light of increasing environmental consciousness and due to rapidly expanding local populations, there is a large increase in the production of liquid and solid wastes together with diminishing options for environmentally sustainable disposal of that waste (Ekama, 1993a; Ekama 1993b).

Due to the limited amount of available water resources, South Africa's current policy is that it needs to utilize effluents as an integral part of its water supply. Effluent producers are therefore required to return effluents to the catchment from which they originated (Water Act of 1956 and National Water Act of 1998). Since most effluents are, however, less suitable to users than the source from which they originate, effluent producers are required to purify their effluents to acceptable standards prior to returning them to their catchment of origin. For various reasons it is often not possible to enforce this requirement, and for these cases a permit of exemption (or licence), which allows discharge of effluent to land for a limited period, is issued by the Department of Water Affairs and Forestry (McConkey, 1997).

Where it is not feasible to treat an effluent to the standard required for return to the point of abstraction of the original fresh water, other options may be promoted, such as the reuse of the effluent with or without pretreatment (dependent on the characteristics of the effluent). If the effluent is pathogenic, the health regulations (Department of National Health and Population Development, 1978) may be used to help determine what reuse options are acceptable. Reuse of effluents may be for industrial or agricultural purposes. In the case of the latter, organic and nutrient contaminants as well as the moisture in effluent can be beneficially utilized for growing crops and grasses. The organic content, if significant, helps to improve soil structure and also performs as a slow-release fertilizer, and the nutrients supply immediate plant nutrient needs. Thus the reuse of such effluents results in a saving on fertilizers. The moisture in effluent may be used in place of irrigating with fresh water: "By utilising moisture in effluent, fresh water which would normally be required for agriculture may be saved for other use." (Shuval et al., 1986). A need is believed to exist for extending the existing guidelines on applying effluents to land for beneficial purposes, in South Africa.

There are several options to consider when applying effluent to land: to **supply crop nutrient** requirements; to **supply crop water** requirements or to **treat the effluent** by employing the filtering capabilities and chemical attenuation characteristics of soil and vegetation. A further option, **disposal of effluent** to land, should preferably be the last option made available to effluent producers, and where practised, it needs to be done without an unacceptable negative impact occurring on water resources or on the environment. In most countries, the major objective of effluent to land applications is the discharge of effluent at minimal cost/impact to (a) the effluent generator, (b) human health, and (c) the receiving environment (Shuval et al., 1986; WHO, 1995). Guidelines therefore need to address the issues of crop nutrient and water requirements, on-land effluent treatment options and the impact of effluent application to land on human health and on the receiving environment.

A suggested procedure for doing an effluent-to-land suitability study has been drawn up. The framework of this procedure is similar to that for sewage sludge in South Africa, the United States, and many other countries, however, there are some differences in terms of applicable limits, priority contaminants and resources at risk. The procedure is designed to facilitate a permitting process, and assesses the suitability of an effluent for application to land, dependent on:

(a) effluent pathogen characteristics/treatment stage and application/crop type, in accordance with health guidelines (for example: Department of National Health and Population Development, 1978);

(b) the required site-specific characteristics on which to base a judgement in terms of acceptable slope, depth-to-groundwater, distance to residences, geology, and soil characteristics (amongst others); and

(c) acceptable application rates dependent on crop nutrient requirements, contaminant loading rates and climatic water-balance limitations;

specifying applicable design, planning and management measures. The suggested procedure is presented in more detail as follows:

Effluent/ land-use acceptability criteria:

Identify relevant effluent/ crop-type and land-use characteristics. Determine if the combination is acceptable or not in terms of health guidelines. If acceptable, indicate what restrictions or protective measures (if any) are required. Unacceptable combinations represent overriding criteria.

Effluent/ crop, climate and site criteria: Identification of further overriding criteria, limiting conditions and relevant corrective measures:

(i) Information-gathering:

- ❏ Obtain effluent analysis and soils analysis data.
- ❏ Obtain relevant information on topography and climate.
- ❏ Identify key/ important criteria on geology, geohydrology and hydrology.
- ❏ Identify other important site criteria, e.g. adjacent land-uses, land-zoning, site access, etc., and measure relevant separation distances.
- ❏ Identify suitable crops or else select and assess the crop types that have been specified by site owner/manager.

- ❑ Obtain seasonal crop factors and nutrient requirements of the relevant crop(s) taking into account crop growth characteristics and expected nutrient removal at harvest.

- ❑ Obtain data on effluent application area(s) and monthly volumetric effluent discharges.

(ii) Derivation of results:

- ❑ Derive monthly climatic "water-balance" criteria, taking into account leaching and crop factors.

- ❑ For soil, derive current (bioavailable) toxic contaminant levels and also residual N in soil.

- ❑ Derive nutrient, organic, contaminant and moisture application rates.

- ❑ Determine if any limits have been overstepped in terms of nutrient, contaminant and moisture application rates, and if so, by how much.

- ❑ If any limiting condition is overstepped, determine percentage reduction requirements on effluent in order to satisfy each of the limiting conditions.

- ❑ Present options on how to address relevant limiting conditions.

- ❑ Allow changes to be made to effluent application rates and crops to be grown.

- ❑ Re-assess to what extent any potential limiting conditions may be overstepped, then allow further changes and reassessments to be made until a suitable application rate and crop type is found.

- ❑ Consider any mitigatory measures that may be applicable, and recommend those that are most suitable, if the required effluent application rates are to be allowed.

Reporting requirements: Identify overriding and other important issues and link each to relevant regulatory conditions as well as mitigatory measures, where applicable, and attach relevant recommendations and/or other advice.

- ❑ Indicate whether effluent-type and land-use/ crop type combination is acceptable.

- ❑ Taking into account the type of ownership /control over site, do the following:

  - ➪ Indicate whether the required effluent volume application patterns, etc. are acceptable.

  - ➪ Indicate whether effluent/soils analysis results and important site criteria are acceptable.

- ➪ Highlight potential problems relating to other site criteria.

- ➪ If the proposed effluent application to land is acceptable, list relevant planning/design/management measures.

- ➪ If the proposed effluent application to land is not acceptable in its current form, indicate why not, and list what conditions, if any, could be required for the proposal to be reviewed.

In the light of increasing environmental consciousness and due to the rapidly expanding populations in South Africa, there is a large increase in the production of liquid and solid wastes together with diminishing options for environmentally sustainable disposal of that waste. The need for guidelines for effluent application to land is becoming more acute, and as these guidelines are necessarily complex, there is believed to be a need for such guidelines to be incorporated in user-friendly software. Software which supplies tools to help in guideline interpretation and implementation, if this is integrated with some form of routine "intelligence", should be of value to potential users, as such users are not likely to have all the expertise needed in order to interpret and implement the guidelines. The development of expert system s-based decision support tools is believed to be a way of obtaining such software.

1.2 Study objectives

The overall objective of the research project is to develop expert systems incorporating guidelines and advice on land-based effluent disposal and effluent use, together with relevant decision-making processes, in order to provide decision-makers with appropriate, readily accessible information and expertise on personal computers.

Aims:

- ❏ Develop an expert system to give advice and to present regulatory conditions for effluent disposal-to-land permitting purposes.

- ❏ Develop an expert system whose purpose is to present relevant guidelines and to give advice on the beneficial use of effluent for agriculture and forestry.

- ❏ Develop an expert system to help select cost-effective sewage treatment and effluent to land disposal facilities for communal purposes (e.g. schools, day-care centres, clinics, shopping areas) in rural developing communities.

- ❏ Identify a suitable IEM strategy for effluent-disposal or effluent use permitting purposes, and determine how this strategy may be used to underpin the permitting process. Develop a coordinating expert system whose functions are to give advice on the permitting strategy, to give other supporting information and to call up the other expert systems.

1.3 Expert-systems-based decision support

Modern expert systems are computer programs which are designed to provide certain types of expertise as well as other forms of decision support, where the latter are driven by, or else incorporate "routine intelligence". Several computer-based decision support systems have been developed as a major part of this project to provide the required decision support for permitting officials and others who are involved in tasks relating to the effluent application to land.

The decision support programs developed for this project include:

- ❑ A health permitting tool for sewage effluent.
- ❑ A site-assessment advisor for sewage effluent, which may also have applicability for organic effluents.
- ❑ Soil contaminant limits assessment component.
- ❑ Monthly precipitation-evaporation assessment tool.
- ❑ Effluent application rate assistant.
- ❑ Crop selection assistant for crops (addresses crop sensitivity to TDS, Cl and B).
- ❑ Sewage effluent health risk versus cost comparative assessor
- ❑ Sewage treatment system option selection assistant

These are described in some detail in **Chapter 10**.

2 EFFLUENT/SOILS CHARACTERIZATION FOR LAND-APPLICATION PURPOSES

In order to begin to characterize effluents for land-application purposes, it is worthwhile to consider existing guidelines which categorize effluents in terms of their application to land. This needs to be done in order to see in what way they can be utilized within a larger set of guidelines, and where possible, to distill the inherent expertise contained in them and to utilize this in the enlarged guidelines. The characterization of an effluent needs to be seen in terms of the objectives to be achieved and the issues which relate to these. Once a decision has been made to discharge effluent to land, the major objective is to protect the health of human populations at risk. The most important issues relate to the pathogen content of effluents together with the associated health risk presented in terms of the land-use application (Blumenthal, 1988).

In terms of volume, the most significant liquid wastes (effluents) in South Africa are (Thompson, 1985; Department of Water Affairs and Forestry, 1993):

(i) sewage effluents,
(ii) acid sulphate waters from the mining industry,
(iii) irrigation return flows,
(iv) effluents from industrial sources.

The primary concern with sewage effluents is the fact that they contain significant and diverse quantities of human pathogens and have a fairly high chemical oxygen demand (Metcalfe and Eddy, 1991; Asano, 1994). These aspects, together with the large volume of sewage generated, represent a problem in terms of treatment and discharge (Ekama, 1993a; Metcalfe and Eddy, 1991). However, sewage effluents, along with organic and nitrogenous effluents from certain industries, should be considered as being more of an asset than a liability in water-limited countries such as South Africa, once they are treated according to certain standards, since such effluents contain plant nutrients and so may be used to irrigate and fertilize crops, pastures and trees (Thompson, 1985; Shuval et al., 1986). Such utilization can save on fertilizers and help prevent potential eutrophication of surface waters, the latter which is likely to occur as a result of the discharge of conventionally treated effluent to surface waters (Thompson, 1985; WHO, 1995).

The most serious threat of mine waters is presented through the impact of acidification of soils and surface waters. Such waters generally need to be treated for acidity and certain dissolved metals (CSIR,1991). Land application of acidic effluents significantly reduces the potential attenuation capabilities of soil for heavy metals, and consequently increases the pollution threat of such effluents for plants, soils and water resources. It is recommended that acidic effluents be first corrected to a pH of at least 6 before being applied to land.

Irrigation return flows are usually high in TDS and nutrient concentrations. Although it is possible to remove nutrients from such water, very little can be done about salinity, and it is the latter aspect that generally presents intractable problems for soils, crops and water resources (Thompson, 1985). These effluents are not addressed in much detail in the current study, because:

- Well-researched and comprehensive guidelines for irrigating with slightly saline water exist;

- Highly saline waters should not be used for irrigation purposes because of their impact on plants and soils (Thompson, 1985); and

- Saline effluent needs to be applied at high rates to prevent the build-up of salinity in soils. High salinity and high leaching rates reduce a soil's ability to treat soluble contaminants in effluent (Oliver et al., 1996; Thompson, 1985).

The effects of high sodium levels on soils and plants have not been addressed in this study, for reasons similar to those given above (sodium contributes to salinity). Guidelines on the effects of sodium on soils and woody plants can be found in Hanson et al. (1993).

Many industries produce effluents which have a significant concentration of potentially hazardous trace elements which are difficult to treat and which cause long-term discharge problems (WHO, 1995). These effluents sometimes contain high concentrations of total dissolved solids (TDS), which represents salinity. One of the major problems with industrial effluents is their diverse nature (Thompson, 1985).

Thompson's classification for effluent discharge to land

Thompson (1985) developed land-application guidelines for effluents which are utilized by government permitting authorities in South Africa. These guidelines rate certain types of soil on the basis of their suitability for the application of each of four classes of effluent. The effluent classes are:

1. Sewage effluents, processed and upgraded to different levels, usually little contaminated with toxic industrial wastes.

2. Ammoniacal and ammonium salt-rich effluents with or without appreciable amounts of other salts and/or organic matter.

3. Effluents with high organic matter content but relatively low sodium adsorption ratio (SAR). Total dissolved salts (TDS) are not usually very high due to the presence of mineral salts, but salinity due to soluble organic compounds may be.

4. Alkaline effluents with a high sodium-adsorption ratio (SAR), often with large amounts of dissolved organic matter and/or high TDS due to mineral salts.

Thompson's categorization of effluents is believed to be useful in terms of identifying suitable soils on which to apply effluent from a specific class. The guidelines address effluent treatment, soil conservation, salinization problems, and the effects an effluent solution has on soil pH and hence on the mobility of contaminants in a soil. Thompson's guidelines do not address pathogens, particular trace elements or organic chemicals in any detail. In the light of the effluent and soils characterization study done as part of the current project, it is suggested that a change could be made to Thompson's classification, for food chain and groundwater impact purposes, by broadening the second category to include nitrogenous effluents, by splitting the fourth effluent class into high-TDS effluents and alkaline effluents and also by adding two further classes, acidic effluents and special class effluents.

- ❏ The reason for changing the second category to nitrogenous is that nitrogenous organic substances are mostly degraded to ammonium compounds (Canter and Knox, 1986), and in the presence of oxygen, ammonia is eventually oxidized to nitrate. Nitrates present a serious contamination risk for groundwater (Canter and Knox, 1986). Thompson's guidelines address the acidification potential of ammonium ions. As ammonia and nitrates are potential plant nutrients, a further addition of another potential nutrient, phosphorus, could have been considered to form part of this category from a surface water pollution point of view. However, the guidelines only address effluents from a land application perspective, and as phosphorus is effectively bound by soils, the risk of water pollution from phosphorus in effluent is not considered to be a major issue for properly managed irrigation sites.

- ❏ The reason for splitting the fourth class into two is that high-TDS effluents are likely to have a significant impact on crop growth and on good-quality aquifers, whereas some alkaline effluents are unlikely to have direct, significant negative impacts on aquifers or on crops. Such effluents are more likely they will have direct affects on soil. (Hanson et al., 1993; Adriano, 1986)

- ❏ The need for an acid effluent category is that acidic effluents represent a large volume of effluents which have a significant pollution potential if left untreated.

- ❏ Special-class effluents include effluents with the potential to contaminate the food chain and groundwater, for example, those effluents which have a significant concentration of heavy metals, boron, fluoride or organic chemicals.

The suggested categories are:

1. Sewage effluents, processed and upgraded to different levels.

2. Nitrogenous effluents (including ammoniacal and ammonium salt-rich effluents).

3. Organic matter(OM) effluents: effluents with high organic content.

4. Alkaline effluents.

5. Acidic effluents.

6. High TDS effluents.

7. Special-class effluents.

(More than one category can be used to describe an effluent.)

Classification of sewage effluents from a health perspective

A health-related classification system for sewage, which depends on the treatment process applied, is used for regulatory purposes in South Africa (Department of National Health and Population Development, 1978). This system indicates to what extent the treated sewage is considered safe in terms of human pathogens, for specific land-use application. It also indicates to what extent the sewage is likely to be noxious. For example, partially treated sewage is able to degrade further, it is potentially capable of producing obnoxious odours and attracting flies, and it is able to foster the re-growth of certain pathogens (Shuval et al., 1986; Metcalf & Eddy Inc., 1991). Similar classification systems for sewage are used by many nations, however, it is generally recognized that a specific treatment process will not guarantee the production of an effluent that falls within pre-defined pathogenic/COD limits (Ekama, 1995), and so regular sampling of effluent for pathogens, nutrients and COD is often a further requirement. Even with these drawbacks, this classification system is useful from a land-use/ human health perspective (Blumenthal, 1988; Hespanhol, 1990), and should also be found useful if applied to other organic effluents which contain pathogens.

Effluent and soils characterization from effluent treatment, human health, crop protection and water resource protection perspectives

An attempt has been made in this study to characterize effluent and soils in some detail in order to facilitate the planning and management of effluent application to land. The effluent characterization needs to account for the potential risk that contaminants in effluent might have on humans, animals, plants, animals and water resources. The soils characterization needs to be able to describe the potential ability of soils to attenuate contaminants in effluent, given a few key soil characteristics.

A literature survey shows that mobility and bioavailability of specific contaminant species in soil are found to depend on:

(i) whether they are inorganic: anionic or else inorganic: cation-forming,

(ii) the valency of the inorganic ionic species,

(iii) the molecular size or volatility of organic contaminants,

(iii) whether organic contaminants are polar (ionizable) or non-polar,

(iv) the individual characteristics of the contaminant species, and

(v) the effect the effluent/soil solution has in terms of the mobility or bioavailability of individual contaminants.

(Oliver et al., 1996; Adriano, 1986; Fuller, 1978; Canter and Knox, 1986; Domenico and Schwartz, 1990; Benjamin et al., 1996; Tanji and Valoppi, 1989; Bouwer, 1985)

The overriding factor which influences the mobility or bioavailability of ionic contaminants in soil is pH, where low pH mobilizes cationic contaminants and high pH mobilizes anionic contaminants in a soil solution (Allen, 1997). Secondary factors are the soil media type, where organic carbon, non-kaolinitic/kaolinitic clays, iron/ manganese oxides/oxy-hydroxides and carbonate soils are most effective in attenuating cationic contaminants in low and neutral pH conditions, and to a lesser extent in attenuating anionic contaminants in neutral to high pH conditions (Sililo et al., 1999). Organic carbon is most effective in attenuating many heavy metals and non-volatile organic chemicals (Allen, 1997; Oliver et al., 1996; Adriano, 1986; Fuller, 1978; Domenico and Schwartz, 1990; Benjamin et al., 1996; Lerner, 1996).

Effluent characterization

Contaminant mobility, as well as the availability of these contaminants to plants, is dependent on the contaminant, its concentration in the effluent, on other effluent chemical characteristics, and on soil media properties, amongst others (Sililo et al., 1999; Smith, 1996; Chaney, 1990a).

It is therefore important that an effluent characterization incorporates information relating to the type and concentration of contaminant found in an effluent (Ekama, 1995). This usually requires that effluent analyses be available. When an analysis is not available, other readily available information could be used to produce some of the required information. In this case a large degree of error is introduced, so there needs to be some indication whether the results are supported by an analysis or not.

For effluent irrigation purposes, a two-level characterization is suggested which could address, at the first level, "broad-category" information which could be used for:

- preliminary planning and mapping purposes, and/or
- effluent irrigation feasibility studies.

At this level, both the current health guidelines and, possibly, Thompson's guidelines, could find a home. Effluent content detail and related information would then be addressed at the second level. This second level could be used for (for example):

- site design and management purposes,
- permit exemption application purposes.

An example of the characterization that could be used at the first and second levels, follows :

FIRST LEVEL (effluent category information [most categories can be defined as High, Medium or Low])

(i) (Pre-)Treatment type/ pathogenic-content category.
(ii) Acid-forming/ alkali-forming potential of effluent (in soil).
(iii) Salinity and SAR categories.
(iv) Degradability category.
(v) Nutrient-content category.
(vi) Turbidity/ suspended-solids categories.
(vii) Oils, greases and detergent content categories.
(viii) Toxicity types and rating. e.g. medium-risk (carcinogenic): Mammalian - soil ingestion route.

SECOND LEVEL (data/ complementary information)
(i) Pathogen types/ content.
(ii) Temperature, pH, alkalinity.
(iii) TDS value and macro constituents such as Na, Cl, etc.
(iv) BOD, COD, TOC concentrations.
(v) Nutrient concentrations (e.g. nitrate[N], ammonia [N], orthophosphate [as P]).
(vi) Suspended solids, type and content (e.g. inorganic, algae, other organics.)
(vii) Oils and greases, detergents.
(viii) Priority contaminant concentrations (e.g. mercury, cadmium, lead, cyanide, arsenic, selenium, boron, fluoride, PCBs).

Soil characterization

Adsorption of ionic contaminants by soil is highly influenced by soil and effluent pH (Allen, 1997). For medium-pH soils, sorption is effective if soils have a high proportion of clay, organic carbon, carbonates or sesquioxides. Adsorption and degradation of organic chemicals are heavily influenced by a soil's organic carbon content (Sililo et al., 1999).

Following a similar argument to that used for effluent characterization, a soil characterization suitable for effluent discharge purposes could also consist of two levels, with categorical information at the first level and content detail at the second level. An example follows:

FIRST LEVEL (soil category information)
(i) % clay content category.
(ii) Buffered soils or leached soils.
(iii) Presence of calcium and/or carbonates (answered as Yes or No).
(iv) Red or yellow or "low chroma" soils; dark or light-coloured soils.
(v) Physical characteristics such as shallow/deep soils, layering, etc.
(vi) Maximum residual contaminant threshold excess, which is the estimated percentage by which a cumulative contaminant loading exceeds, or falls short of, a prescribed limit for the total load of a particular contaminant of concern. The contaminant which most exceeds the limit is the one whose value is used. (Note on percentage excess: a **minus {-}** indicates percentage below threshold)

SECOND LEVEL (soil-media analysis data/ complementary information)
(i) Clay type and % content.
(ii) Soil salinity, sodium-absorption ratio and acidity.
(iii) % content of calcium and/or carbonates.
(iv) % content iron/manganese oxides/hydroxy-oxides.
(v) % organic carbon content.
(vi) Depth to groundwater, site slope, soil depth and soil-layering details.
(vii) Measured concentrations of residual contaminants (These are used to compare with the maximum concentrations allowed).

The above characteristics are believed to relate directly to a soil's attenuation potential (Sililo et al., 1999). The most important factor controlling the attenuation of inorganic contaminants in soils is soil pH (Allen, 1997). A soil with high attenuation potential for effluents with significant concentrations of trace elements would be a deep unsaturated one with a neutral pH and a high organic carbon, calcium, sesquioxide and non-kaolinitic clay content. A soil with high attenuation potential for non-volatile organic chemical effluents would be an unsaturated one which has a high organic carbon content (see **Chapter 3** and **Chapter 6** of this report). A suitable soil for nitrate attenuation would probably be a duplex soil (a permeable upper layer, preferably deep, and an impermeable lower layer) with a fairly high organic carbon content and planted with deep-rooted plants (see **Chapter 6** of this report). Pathogens in effluents are likely to be attenuated most effectively by unsaturated soils with a high carbon content as well as a high proportion of clays and iron/manganese oxides/oxyhydroxides (e.g. dark red, clayey soils) (see **Chapter 6** and **Chapter 8** of this report).

It is suggested that, in order to interpret known soil types (such as those addressed by the South African Soil Taxonomic Classification System) in terms of their relative attenuation potential, specific soil forms, families and/or series could be linked to analytical data categories at the second level, in the form of data ranges. If such information is lacking for some categories, or the ranges are too large, links to relevant soil-category information at the first level could be considered.

It should be noted that the physical characteristics of soils such as the existence of horizontal layers of different permeability (e.g. in duplex soils), preferential flow pathways (e.g. presence of fissures, wormholes, channels left by decayed root systems, etc.), shallow soils overlying bedrock, and other factors such as site topography, can make the physical characterization of soils very complex from a contaminant attenuation perspective. This is especially relevant as contaminant attenuation is dependent on pathway characteristics. In duplex soils this can mean that much of the effluent will travel downslope (just below the soil surface, above the impermeable subsoil layer), instead of vertically, thus increasing its travel time through the soil. The effluent will take much longer to reach groundwater and so will be attenuated more effectively than effluent which travels directly down to the groundwater. Generally, when the time-of-travel through the soil is increased, the potential for attenuation is increased. On the other hand, shortcuts to groundwater via worm holes, root channels and fissures, reduce the time of travel significantly, resulting in a reduction in contaminant attenuation potential of affected soils (Sililo et al., 1999).

3 EFFLUENT APPLICATION TO LAND: OBJECTIVES, OPTIONS AND CONSTRAINTS

A philosophy which is accepted by many "water stressed" nations in the world to support the need to utilize effluents on land in place of using fresh water, may be expressed in the following statement: “By utilising moisture in effluent, fresh water which would normally be required for agriculture may be saved for other use.” (Shuval et al., 1986).

In most effluent to land applications the major objective is the discharge of effluent at minimal cost/impact to (a) the effluent generator, (b) human health and (c) the receiving environment (Shuval et al., 1986; WHO, 1995). Aims (i) to (iii), below, may be considered alternative options, used either to reduce financial costs, to help protect human health, or to reduce environmental impact. We now discuss these.

There are several options which may be considered in the application of effluent to land (Shuval et al., 1986; Broadbent and Reisenhauer, 1990; Bouwer, 1985):

(i) to **discharge as much effluent as possible** to land without an unacceptable negative impact occurring on land, water resources or the neighbouring environment,

(ii) to **supply crop nutrient** requirements,

(iii) to **supply crop water** requirements (*ie*: to recharge depleted soil moisture in the root zone of crops),

(iv) to **treat the effluent** by employing the filtering capabilities and chemical attenuation characteristics of soil and vegetation.

Conventional treatment cannot remove all the nutrients or pathogens in wastewater that soil and vegetation can (Bouwer, 1985; Shuval et al., 1986). By utilising nitrogen and other nutrients in percolating effluent, managed crops help cleanse the effluent water of nutrients and in so doing, save on the cost of effluent treatment and on the cost of fertilizers. Chlorination of treated effluent from a conventional treatment system forms tri-halomethanes (THMs) which are known to present a risk to in-stream ecosystems and to a lesser extent, a cancer risk when used for drinking water purposes (Khouri et al., 1994). Treatment by soils is a viable, low-cost alternative to conventional treatment (Bouwer, 1985).

In order to supply the water requirements of plants, to apply as much effluent to land as possible, to recharge an aquifer or to use vegetation and soils to treat the water to an acceptable standard, information on monthly precipitation, evaporation, seasonal crop growth, topography and effluent volumes is required. If daily values are available, they should preferably be used (Van Eeden, 1998).

Effluent application: Overriding and limiting conditions

Various overriding and limiting conditions may prevent or restrict effluent application to land.

Overriding conditions are those which act as "red flags", which do not allow any effluent to be applied to the land in question. Limiting conditions are those which restrict the allowable application rate of effluent to land. Overriding conditions usually need to be addressed "upfront" so that as little effort as possible is wasted in the administration process, should such a condition exist. Limiting conditions need to be determined from a range of potential restrictions on the maximum allowable application rate of effluent to land. Once they are assessed, the most conservative limiting condition is the one used to identify the maximum allowable application rate.

Most overriding conditions for effluent application to land are applicable to sewage effluents, because the high pathogen content of such effluents has prime consideration. These usually are addressed first from a permitting standpoint. Other overriding conditions relate to high levels of potentially toxic substances in the effluent itself, and in site soils. Other conditions have the potential to be overriding, depending on whether suitable mitigatory measures are applicable or not. These are discussed further hereunder.

Potential overriding conditions:

Potentially toxic substances in soils:

When applied to land in effluent or sludges over the years, certain potentially toxic substances build up in soils to levels which represent a toxic risk to plants and animals. In the South African sludge to land guidelines, prescribed limits are set for such substances commonly found in sewage sludge (WRC, 1997). If the application of a substance (such as cadmium) causes the concentration of that substance to build up to overstep its prescribed limit for soil, then no more should be applied to the land in question. This is potentially a very significant overriding condition, as some soils in South Africa (notably shales), naturally contain potentially toxic elements which exceed their prescribed limits (WRC, 1997). A major issue here is that a large proportion of the elements in soil and sewage sludge are not in a bioavailable form, having strong chemical bonds to the molecules that make up the soil and sludge particles (Chaney 1990a; Chaney 1990b; Fey, 1990; Smith, 1996). It seems illogical to consider that such substances in their non-bioavailable form will present a significant risk to the environment even at relatively high concentration levels. It is therefore recommended that tests on soils be those that test for bioavailable concentrations of potentially toxic trace substances.

Some plants, animals (e.g. soil biota) and water resources may be susceptible to high concentrations of certain substances in effluent (as opposed to the application rate of such substances). Examples of such substances are boron, molybdenum and chlorides (Ayers and Wescott, 1985; Page and Chang, 1990). It is recommended that maximum concentration limits in effluent be set for such substances, dependent on land-use category. Examples of a further two substances which may be added to this list are cadmium and mercury, due to the susceptibility of soil biota to these contaminants (Page and Chang, 1990; Chaney, 1990a; Chaney, 1990b) and to the volatility of potentially toxic mercuric compounds. Manuals published by Department of Water Affairs and

Forestry (1996) contain concentration limits for irrigation water relevant to South African conditions. (See the next chapter for further details.)

Distance requirements for residences and surface water features:

Distance requirements, in the form of minimum setback distances, should depend on the nature of the effluent. For sewage effluents, minimum setback distances are prescribed in the literature. For non-sewage effluents, little information on recommended setback distances is available. For effluents which emit odours, setback distances for residential, recreational and commercial areas may be determined on a case-by-case basis, as they would depend on odour emission rates, climatic factors and topographic factors amongst others. Mitigation measures, such as the establishment of buffer strips and berms, may be used to mitigate possible impacts.

Highly saline effluents:

As mentioned elsewhere in this report, highly saline effluents are very problematic to manage. Adversely-impacted soils are usually very difficult to treat, and non-saline water resources in close proximity are usually at risk of becoming more saline (Thompson, 1985). A limit could be set for high salinity levels. For example, EC values above 540 mS/m (maximum given in Department of Water Affairs and Forestry, 1996) could cause an effluent to be excluded from being discharged to land except next to the sea or saltpans. Generally, the effluent application rate, irrigation management, soil type, climate, etc., help to determine the kinds of plant that may be grown (Department of Water Affairs and Forestry, 1996).

Acidic effluents:

Acidic effluents generally should not be applied to land unless the soil is limed (Thompson, 1985). Alternatively, it is recommended that such effluents receive a positive pH adjustment to a value of at least 6 prior to land application. There are exceptional cases where acidic effluents could be applied, such as to soils which have a high content of calcium carbonate, but such cases would need special consideration.

Alkaline effluents:

It is recommended that alkaline effluents are treated so as to reduce the pH to a neutral level before land application is considered. There are exceptional cases where alkaline effluents could be applied to land without prior treatment, such as to acidic sandy soils and where no water resources are likely to be significantly impacted, but, as with acidic effluents, such cases would need special consideration.

Potential overriding conditions relating to acidic and alkaline effluent could also be seen as representing limiting conditions, where low application rates on certain soils may be acceptable.

Limiting conditions are discussed in further detail, below.

Potentially toxic substances in effluent:

The potential toxicity of a potentially toxic substance depends on the application rate of that substance to land, amongst other factors (Smith, 1996). For such a substance in effluent, the potential toxicity would then depend on the application rate of the effluent and the concentration of that substance in the effluent. The annual application rate of a substance may not exceed the prescribed application rate limit for that substance (WRC, 1997). This represents a limiting condition for applying effluent.

If the land application rate of certain potentially toxic trace substances in effluent is exceeded, the application rate of effluent would normally need to be restricted so that no limits are overstepped. In some cases, the most limiting restriction may be for a land-use that is not relevant (e.g. the most restrictive limit is for soil ingestion by cattle, but the application being considered is for crop production), and in this case the restriction could be lifted. Even for crop production, the sensitivity of plants to potentially phytotoxic trace substances varies between types of plant, and it is recommended that the type of plant growing at a site be considered when phytotoxic substances are likely to restrict effluent application rates to land. In general when considering such limits, assume all the limits apply unless proof exists to show that one or more limits are not relevant or else that the associated risk is acceptable. In the latter case, if the most limiting restriction relates to crops, and the crop owner is happy to take the risk of a failed harvest, a relaxation of this limit could be granted once all other related issues have been given proper consideration.

Moisture requirements of plants; leaching and evaporation “requirements” of a site:

If plant moisture requirements and leaching and evaporative requirements are met for a specific effluent application rate, any extra application of effluent may be considered excessive. This application rate could set a limiting condition.

Mobility of nutrients and other potential contaminants in soils:

Certain potential contaminants are relatively mobile in soils, and may be readily leached out of topsoils into the groundwater underneath, or else could travel downslope in the subsoils to become concentrated at some location, or could eventually enter a surface water channel or related feature. Mobility depends on several factors: the contaminating substance, soil type, soil aeration, soil pH, and others. Nitrates, boron, selenium, arsenic, cyanide and fluorides are usually fairly mobile in sandy soils (Sililo et al., 1999; Bouwer, 1985).

In order to manage the application of effluents to vegetated land so as to supply crop nitrogen needs, the seasonal nitrogen requirements of plants should be matched to the nitrogen made available to plants from irrigated effluent (Pettygrove and Asano, 1990). The ability of plants to take up nutrients depends on many factors, and expert advice is often necessary. In order to determine the required nutrient supply and associated management methods. Phosphates in effluent are readily adsorbed by soils, but nitrates are very mobile and may be easily leached to a depth beyond the root zone of plants (Burt and Haycock, 1993; Bouwer, 1985). If anoxic conditions exist in the soil, given sufficient available carbon in the soil or effluent, denitrifying bacteria will proliferate and denitrify much of the percolating nitrates. Otherwise the nitrates will eventually percolate down to the groundwater and there they could build up concentrations in groundwater to levels which represent a risk to babies and to pregnant animals (Van Eeden, 1998), if the water is abstracted for drinking purposes. If nitrogen application rates in irrigated effluent exceed plant nitrogen requirements, the excess nitrogen may be - or else may become - mobile (as nitrate). The corresponding effluent application rate may be considered excessive. Nitrogen could then represent a limiting condition in terms of effluent application rates.

Constraints on the application rate of effluent to land for beneficial purposes therefore relate to:

- the moisture requirements of plants and the seasonal water balance,
- the annual nitrogen requirements of plants,
- the leachability of contaminants to groundwater and surface water resources,
- the prescribed land application rate limits for potentially toxic substances in effluent,
- possibly, acidic and alkaline effluents,
- possibly, macro element concentrations in effluent, and
- possibly other factors such as biological oxygen demand (BOD) of the effluent (this is highly dependent on site-specific and irrigation management factors).

4 CONTAMINANTS: POTENTIAL IMPACT ON PLANTS, ANIMALS AND WATER RESOURCES

Crops may be split into groups according to their sensitivity to salinity in irrigated effluent, to concentrations of specific ions in the effluent, to their requirements for nutrients and their need for water (Department of Water Affairs and Forestry, 1996; Ayers and Wescott, 1985). Generally crops are also sensitive to the BOD (biological oxygen demand) and pH of the effluent, due to the effect these have on the availability of soil oxygen and trace elements to crops. Although pathogens are not taken up by crops, certain zootoxic trace elements in the irrigated effluent are. (Smith, 1996; Idema and Rodda, 1994; WHO, 1995; Pescod and Arar, 1985; Shuval et al., 1986; Hanson et al., 1993)

- Zootoxic trace elements include antimony, arsenic, cadmium, chromium, cyanide, lead, mercury, molybdenum, nickel, selenium, tin (Department of Water Affairs and Forestry, 1996). Some of these are often found in effluents at levels indicating a significant health risk to animal life, and they may be prioritised accordingly. Mercury heads the priority rating (Department of Water Affairs and Forestry, 1993), followed by cadmium, arsenic, lead, selenium and silver. The priority of the latter group is based on monthly monitoring requirements (Kempster and Smith, 1985).

- Phytotoxic trace elements include arsenic, boron, cadmium, chromium, copper, fluoride, nickel, and zinc (Department of Water Affairs and Forestry, 1996). Many of these are essential for plant growth in small quantities, but become potentially phytotoxic when they exceed certain concentration thresholds (Smith, 1996; Ayers and Wescott, 1985). The gap required between the minimum concentration required for healthy growth and the maximum concentration before toxic effects occur is fairly large for most trace elements and for most crops, a noteworthy exception being boron. Boron is singled out as requiring attention when applying effluent to crops as it is commonly found in such high concentrations in effluent as to present a significant risk to crops (Hanson et al., 1993; Department of Water Affairs and Forestry, 1996). Boron is also a highly mobile trace element, and has significant potential to contaminate groundwater (Bouwer, 1985). The sensitivity of plants to boron concentration in irrigation water is given in **Table 6** in the appendix.

- Problematic macro elements (ions) for plants, and to a lesser extent for animals, are chloride and sodium (Ayers and Wescott, 1985; Department of Water Affairs and Forestry, 1993). High chloride ion concentrations affect plant health, whereas high sodium ion concentrations mainly affect the permeability of soils containing clay (to a lesser extent and over a longer term, high sodium concentrations also affect the health of woody plants) (Ayers and Wescott, 1985). The sensitivity of plants to chloride concentration in irrigation water is given in **Table 4** in the appendix. Proper irrigation management measures help reduce the negative impact on crops of high concentrations of sodium and chloride ions in irrigation water (Department of Water Affairs and Forestry, 1996).

- The priority list of potentially toxic trace elements in terms of risk to groundwater should include cadmium, arsenic, selenium, boron, molybdenum and possibly mercury (Tanji and Valoppi, 1989; Bouwer, 1985). All these elements except possibly cadmium, are relatively mobile in soils, so assuming their concentrations are at levels normally found in effluent, and that a portion of the irrigated water leaches away from the application area (the latter is usually a requirement of managed irrigation), it is suggested that their concentrations in surface soils will not necessarily build up over time to levels which exceed their allowable threshold concentration limits (also, mercury in soil escapes readily into the atmosphere). It is recommended that limits in soil not be set for arsenic, selenium and boron if their limits in effluent (for irrigation) are adhered to (Pettygrove and Asano, 1990; WHO, 1995). From a groundwater contamination perspective, acidity (low pH) may be considered to be the single most important factor in terms of stimulating the mobility of heavy metals in soil (Allen, 1997). In terms of groundwater pollution risk from effluent containing heavy metal ions, cadmium generally presents the greatest risk, followed by arsenic (Bouwer, 1985).

❑ From an agricultural point of view, other important determinands for effluents include, in ranked order of importance: TDS, pH and COD or BOD (Shuval et al., 1986). Effluents with high TDS (salinity) generally are not toxic to plants, but due to the effect that high TDS has on osmotic pressures within plants, they result in a significantly reduced plant productivity (Ayers and Wescott, 1985). Plants and soil cannot be used to treat salinity (Thompson, 1985).

General sensitivity-categories for crops, based on sensitivity to TDS and concentrations of phytotoxic ions (except for boron and chloride) are as follows (Ayers and Wescott, 1985) :

Sensitive :	Stone-fruit trees, citrus trees, berry fruits, beans, carrots, onions.
Moderately sensitive:	Maize, millet, peanuts, rice, sugarcane, sunflower; most vegetables, watermelon, grape.
Fairly tolerant:	Oats, rye, sorghum, soybean, wheat, squash, red beet, artichoke, fig, olive, papaya, pineapple.
Tolerant:	Barley, cotton, sugarbeet, asparagus, date palm.

5 CROP NUTRIENT REQUIREMENTS

Crop nutrient requirements are dependent on crop yields, soil type, climate and other factors. Nitrogen in effluent is considered to be the key nutrient for selecting crops, based on matching the seasonal nitrogen requirements of a crop with the nitrogen supplied in effluent (Broadbent and Reisenhauer, 1990; Smith, 1996; WHO, 1995). The Fertiliser Society of South Africa has produced a set of guidelines and tables regarding the fertiliser requirements of plants, relevant for South Africa (Misstofvereniging van Suid-Afrika, 1994). When deciding on site-specific requirements, it is recommended that expert opinion on fertilization, agronomic practice and irrigation management be sought (Van Eeden, 1998).

A *first approximation* for estimating crop nitrogen (N) needs can be made by assessing the amount of N removed when a crop is harvested. When assessing an amount of N to be applied to land, account must be taken of the percentage of N lost due to leaching of N beyond the root zone, by denitrification, by volatilization of ammonia, or by other means. Account must also be made of the nitrogen contributed to the soil by leguminous crops such as beans (Broadbent and Reisenhauer, 1990). Broadbent and Reisenhauer (1990) compiled a table which is designed to help in the first approximation of crop nitrogen needs (see next page):

Table 1: Examples of Crop Yields and Nitrogen (N) Requirements

Crop	Component	Ave. Yield t/ha	Approx. N Removal kg N/t of yield	1st Estimate of crop N needs kg/ha
Barley	grain	4.5 (**3 to 12)	21 (**30)	94 (90 - 360)
	straw	5.6	8.5	48
Beans	dry beans	3	39	117
Corn	grain	10	16.5	165
	silage	56	4.5	252
	stover	4.5	10.5	47
Cotton	seed	1.9 (**2 to 4)	39.5 (**50)	75 (100 to 200)
	stalks	1.4	57.5	80
Oats	grain	3	21	63
Rice	grain	7.4	15.5	115
	straw	7.8	5	39
Safflower	grain	3	34.5	104
Sorghum	grain	4.5	21	95
	stover	4	10.5	42
Soyabeans	grain	2.8	67	188
	stover	2.8	23	64
Sugarbeets	beets	67.2	2	134
	tops	67.2	2	134
**Sugar cane		(**10 to 20)	(**20)	(200 to 400)
Wheat	grain	4.5	19.5	88
	straw	7.8	9	70
FRUIT AND NUTS				
Apricot	fruit	18	2	36
Cherry	fruit	9	2.5	22
Grapes	fruit	22.4	1	22
Peach	fruit	35.8	1.5	54
Pear	fruit	33.6	1	34
Plum	fruit	18	3.5	63
Prune	fruit	18	3.5	63
Almond	nut	2	33.5	67
Walnut	nut	2.2	26.5	58
Grapefruit	fruit	24.6	2	49
Orange	fruit	18	2.5	45
Lemon	fruit	29	2	58

Table 1 (Continued)

Crop	Component	Ave. Yield t/ha	Approx. N Removal kg N/t of yield	1st Estimate of crop N needs kg/ha
FRUIT AND NUTS	(Continued)			
Avocado	fruit	5.8	4	23
Olive	fruit	4.7	2	9
Strawberry	fruit	42.6	2	85
VEGETABLES				
Broccoli	heads	11.2	6.5	73
Carrots	roots	42.6	2	85
Potato	tubers	44.8	4	179
Tamato	fruits	56	2	112
	vines	67	1.5	100
GRASSES				
Mixed grass	hay	4.5	23.5	106
Irrigated	pasture	4.5	17	76
Bent		4.9	34.5	169
Bermuda	grass	9	31.5	284
Kentucky	bluegrass	5	31	155
**Kikuyu grass		(**10 to 20)	(**20)	(200 to 400)
** Perennial rye grass		(**10 to 15)	(**25)	(250 to 375)

NOTES:
Source of data: Broadbent and Reisenauer in Pettygrove and Asano, 1990: "Irrigation with reclaimed municipal wastewater", Lewis, MI.
Data marked ** was provided by Mr. Frans Van Eeden (Van Eeden, 1998)
For more detailed information on crop nutrient requirements relevant to South Africa, refer to the Fertilizer Society of South Africa (Misstofvereniging van Suid-Afrika, 1994).
For South Africa, it is generally recommended that pasture grasses be the crop of choice for effluent to land discharge purposes (Van Eeden, 1998).

6 CONTAMINANTS IN SOIL: MOBILITY AND PLANT UPTAKE

Heavy-metal cations in effluents are generally well adsorped by medium and high pH soils. Sorption is very effective if these soils have a high proportion of non-kaolinitic clay, of organic carbon, carbonates or sesquioxides (oxides and oxy-hydroxides of iron and manganese) (Sililo et al., 1999). These trace elements are fairly well adsorped by kaolinitic clays in medium to high pH soils, and are poorly adsorbed by low-pH kaolinitic clays and salicaceous sands/silts, and especially if the latter have a low pH (Adriano, 1986; Fuller, 1978; Tanji and Valoppi, 1989). The contaminant mobility as well as the availability of these contaminants to plants is dependent on the contaminant, its concentration in the soil, and soil media properties (Smith, 1996; Chaney, 1990a). The mobility of contaminants is dependent also on soil-solution characteristics (Oliver et al., 1996; Lerner, 1996; Allen, 1997).

- Anionic inorganic contaminants in effluents (such as arsenates, selenates, molybdates, chromates) are generally fairly well adsorped by low pH soils. Sorption is effective if such soils have a high proportion of non-kaolinitic clay, or of sesquioxides. These contaminants are moderately well adsorped by kaolinitic clay soils which have a low pH, but are generally not adsorbed significantly by high-pH soils containing kaolinitic clays, salicaceous silts and sands. (Tanji and Valoppi, 1989; Adriano, 1986; Fuller, 1978).

- Generally, neutral pH soils with a high proportion of organic carbon, non-kaolinitic clays and iron/manganese oxides and hydroxy-oxides are suitable for the attenuation of potentially toxic/hazardous trace contaminants (Sililo et al., 1999). Examples of such contaminants include heavy metals, selenium, arsenic, cyanide and certain organic chemicals.

- Non-polar, high-density organic chemicals are bound well by humus in soil and most are degraded by soil microbes within a relatively short period of time (Lerner, 1996). Some resist degradation and are problematic, e.g. most highly chlorinated organic chemicals. Low molecular-weight organic chemicals are more mobile, and those which act as solvents are generally very mobile, and the persistent chlorinated ones are known to contaminate groundwater, e.g. chloroform, some polychlorinated ethylenes and ethanes (Lerner, 1996). Non-biodegradeable detergents and some organic solvents are able to bind to heavy metals and carry them deep into the ground, often to end up in groundwater (Oliver et al., 1996; Lerner, 1996)

- Biodegradable organic contaminants are problematic when soluble organic molecules such as fulvic acid bind to heavy metals and transport the latter into the ground (Bouwer, 1985). However, in relatively impermeable or waterlogged soils, reducing conditions convert heavy metals into their sulfide forms, which are insoluble, thus causing them to precipitate out and to be held back in the soil matrix (Smith, 1996; Canter and Knox, 1986; Allen, 1997). Biodegradable organic contaminants also present problems when they are applied to land at high loading rates with insufficient time allowed for soils to dry out between applications. In such cases, anoxic conditions occur at the soil surface, causing plant roots to die and odours to occur. (Shuval et al., 1986; U.S. Environmental Protection Agency, 1992)

- Nitrates are a common contaminant of groundwater. Major contamination sources include fertilizers, feedlots, septic tank soak-aways and on-land effluent discharge (Canter and Knox, 1986; Ministry of Agriculture, Fisheries and Food, 1991; Ekama, 1993b). Suitable soils for nitrate attenuation purposes are ones which cause anoxic conditions to exist within the subsurface, so aiding denitrification (Bouwer, 1985). Such soils are moist clay soils (which are relatively impermeable) or else are soils with a high organic-carbon content which are saturated for most of the year (Thompson, 1985; Smith, 1996). However, ammonium ions are not denitrified under these conditions, and only should oxidising conditions return (as would occur in a following drying cycle) is there an opportunity for ammonia to be converted to nitrates. When or if anoxic conditions return (such as would occur in the next wetting cycle) the opportunity again exists for denitrification of these nitrates (Bouwer, 1985).

High-nitrogen effluents may be treated through uptake of nitrogen by suitable vegetation and by soils which cause anoxic conditions to occur in the subsurface. High nitrogen effluents are most suitably treated if soils are regularly inundated and then allowed to dry out, resulting in a reduction of between a third and a half of the nitrogen by means of denitrification in anoxic soil zones (Bouwer, 1985).

➪ Pathogens in effluents are attenuated by low permeability soils with a high proportion of clays and, most likely, also of iron/manganese oxides/oxy-hydroxides (Bouwer, 1985; Oliver et al., 1996; Canter and Knox, 1986; Shuval et al., 1986; Aller et al., 1987; U.S. Environmental Protection Agency, 1992).

➪ The more mobile a contaminant is, the more it presents a risk in terms of groundwater contamination (Bouwer, 1986). On the other hand, the less mobile a contaminant is, the more the likelihood of build-up of contaminant concentrations in soil to levels which could represent an unacceptable risk factor to plants and animals (the latter from eating plants or ingesting soil) (Korentajer, 1991; Chaney, 1990a; Smith, 1996). However, the risk implied in the latter is usually small when considering agronomic applications (WHO, 1995; Chaney, 1990b; Smith, 1996; Pettygrove and Asano, 1990).

➪ As most potentially toxic inorganic contaminants, such as the heavy metals, are cationic, it is recommended that soils be tested for cation-exchange capacity prior to determining what contaminant application rate limits are applicable for effluents known to contain such contaminants. It is recommended that for heavy-metal contaminants and for soils with a CEC of less than 5 meq/100g, conservative limits that are normally defined for non-calcareous sands, be used. For soils with a CEC of between 5 and 15 meq/100g, limits which are double the most conservative limits, or preferably the following equation, should be used:

$$\text{New limit} = (\text{most conservative limit}) * (\text{CEC} - 1)/4$$

For soils with a CEC greater than 15, use limits which are four times greater than the most conservative limits. (Page and Chang, 1990).

Relative sorption preferences per metal ion type in soil is generally of the following order, from high to low sorption potential: Pb >= Cu > Cd > Ni > Zn (Fuller, 1978; Oliver et al., 1996).

7 CLIMATE, SITE AND SOIL CHARACTERISTICS AND PROTECTIVE MEASURES

Effluent may be applied to land as long as it does not adversely affect human health or pollute surface and groundwater resources (U.S. Environmental Protection Agency, 1992; WHO, 1995). Protection of groundwater is dependent principally on soil, soil-depth, climate, vegetation, slope and effluent characteristics (Smith, 1996; Domenico and Schwartz, 1990). Protection of surface water is dependent on climate, soil, slope, vegetation and effluent characteristics as well as distance to water and the presence of topographical barriers/corridors to the surface water resource (Smith, 1996; Ministry of Agriculture, Fisheries and Food, 1991, Foster, 1987).This report does not address irrigation practice in detail as there are numerous South African publications on irrigation practice which may be used to promote irrigation efficiency and to estimate crop water requirements (Department of Water Affairs and Forestry, 1996; DAWS, 1985).

Of all the parameters considered, climate plays a very important part:

- If potential evapotranspiration is less than precipitation for any month, it may be assumed that water arriving on the land surface during the month will end up in a relatively short period of time either in groundwater or a in a surface water resource. It is therefore unwise to discharge effluent to land during this period unless there is proof that the resulting impact on a water resource is likely to be minimal. For example, a site with minimal slope and with permeable soils over an important aquifer would most likely not be suitable for the application of effluents during such a month unless suitable management and protective measures are in place and/or there is assurance that contamination risk to the aquifer is acceptable (such as may be the case where the benefits of a recharged aquifer exceed the pollution costs).

- Provided there is no ponding of runoff waters, the time of travel of percolating rainfall through a specific depth of unsaturated soil is controlled mainly by climatic factors (Foster, 1987). The drier the climate, the longer the time of travel will be. Assuming that nett precipitation is equal to precipitation minus potential evaporation, it seems logical to infer that travel time is likely to increase dramatically when nett precipitation crosses over from positive to negative, for a significant period of time (Foster, 1987). For non-saline effluents, the contaminant-attenuation potential of a soil is dependent on the travel-time of a contaminant through a specific soil depth (Oliver et al., 1996). One may then infer that, for non-saline effluents, when the total depth of moisture applied uniformly over time at the soil surface is less than the potential evaporation over the same period, the soil's contaminant-attenuation potential will be significantly higher than otherwise (the total depth of moisture includes both rainfall and applied effluent).

If saturated conditions are allowed to predominate in the soil, attenuation processes are likely to be reduced by an order of magnitude or more, and an underground drainage system may be recommended to help restore unsaturated conditions if no suitable alternative exists (Domenico and Schwartz, 1990; Aller et al., 1987; Tanji and Valoppi, 1989).

Although the above refers to monthly time periods, if data for daily time intervals exists, it is far more preferable to do the above calculations on a daily basis (Van Eeden, 1998; DAWS, 1985). The excess application of effluent to land could cause contaminated runoff to occur from the land-area of concern. Berms, cut-off drains and suitable storage facilities are recommended to prevent water running onto the site from adjacent areas, and to ensure that all contaminated runoff ends up in storage (WHO, 1995). Contaminated water in storage may then be re-applied to the land during a period when there is spare evaporative capacity available for this. Most suitable land slope requirements for application of effluents to land, in order to obtain a low risk of runoff or of stagnant pools forming, is between 1/ 1000 and 5/ 1000 (U.S. Environmental Protection Agency, 1992).

High COD or BOD (organic) effluents should not be discharged to soils which have a high groundwater table, or which are naturally moist, at excessive quantities, unless the soils are regularly dried out to prevent the establishment of anaerobic conditions in the top layers of soil. The inundation depth and period over which the effluent is applied should be dependent on the crop grown. Failure to dry out soils regularly helps to produce anaerobic conditions, which kill plant roots and generates obnoxious odours. (Bouwer, 1986; Ministry of Agriculture, Fisheries and Food, 1991; Shuval et al., 1986; Pettygrove and Asano, 1990).

A major drawback to irrigating with high COD (or BOD) effluents, is that oxygen in the soil will be taken up by the degrading organic fraction in the effluent, thus starving plant roots of oxygen. If this is allowed to happen over significant lengths of time, only plants which are capable of withstanding swampy conditions will survive. Hence the importance of allowing regular “drying-out” periods between applications. In high water-table conditions, drains may need to be installed so as to remove excess water.

High-nitrogen effluents may be applied to soils at a rate in excess of crop nitrogen requirements using wetting and drying cycles applicable to high COD effluents, so that denitrification will occur (Bouwer, 1985). Nitrogenous effluents may be treated by applying them to land with low-permeability, high clay content subsoils. The land in question should preferably be planted with vegetation which is capable of rapid uptake of nitrogen from the ground and capable of withstanding anoxic conditions for the period over which the soil is saturated (Pettygrove and Asano, 1990; Tanji and Valoppi, 1989; Thompson, 1985). Approximately a one to two week wetting and two-week drying sequence should help to denitrify up to two-thirds of the nitrate-nitrogen in effluent (Bouwer, 1985). The length of the drying-out period will depend upon soil, site and climatic conditions.

Plants capable of taking up large amounts of nitrogen include certain pasture grasses (e.g. Kikuyu grass), sugar cane and some fast-growing trees (e.g. Eucalyptus). These can take up more than 200 kg/ha.yr (Pettygrove and Asano, 1990; Shuval et al., 1986; Smith, 1996; Poynton, 1984; Abbott, 1996). 200 kg/ha of nitrogen is supplied by one metre depth of effluent with a nitrogen concentration of 20 mg/ℓ (less than this amount is actually available to the plants due to some loss of nitrogen through leaching and denitrification). An average 20 mg/ℓ nitrogen concentration is typical of secondary treated sewage waters (Khouri et al., 1994; Shuval et al., 1986; Bouwer, 1985).

A major drawback of applying nitrogen at rates which exceed crop requirements would be that the green parts of plants will tend to grow rapidly at the expense of fruit, seed, root development and plant strength (Thompson, 1985; WHO, 1995; Metcalfe and Eddy, 1991). Grass is the least likely to suffer from too much nitrogen. Another drawback is that plants will not take up the excess nitrogen, allowing it to migrate downwards into the groundwater. It is preferable to grow plants whose seasonal nitrogen requirements most closely match the nitrogen supplied by the effluent (Pettygrove and Asano, 1990). Hence perennial plants which grow rapidly in summer and are dormant in winter are normally not suitable for effluents which are discharged during winter months.

When the objective is to discharge as much effluent to land as possible, the typical application rate is 2,5 m/a and upwards, which is considerably in excess of crop water requirements, and in excess of the annual evaporative capacity of all except perhaps the most arid of climates (Shuval et al., 1986). For most effluents this would exceed crop nitrogen requirements, and denitrification would then most likely be the only alternative available for removing nitrate-nitrogen from the effluent before it reaches groundwater (Bouwer, 1985). Under such high application rates, saturated conditions are likely to occur in the soil for much of the time. The institution of wetting/drying cycles to achieve maximum denitrification would then be a necessary management goal. Saturated conditions reduce the attenuation capacity of soil for trace contaminants by up to an order of magnitude, in comparison with unsaturated conditions (Domenico and Schwartz 1990), so the institution of wetting/drying cycles should effectively mitigate the reduced attenuation effects for trace contaminants. Artificial subsurface drainage is normally required to help achieve this management goal (Van Eeden, 1998; Shuval et al., 1986). It is not recommended that such high effluent application rates be used on permeable subsoils overlying important aquifers unless an in-depth investigation shows that the overall impact on groundwater resources is not negative (such as in the case where the benefits of a recharged aquifer exceed the pollution costs).

Discharge of saline effluents on land presents special problems, as no soils can be considered suitable for treating saline effluents (Bouwer, 1985; Thompson, 1985; Tanji and Valoppi, 1989). If soils and vegetation are used to treat contaminants in saline effluent, it would probably be best to consider soils, vegetation and water resources which are not irretrievably impacted by the application of these effluents (Bouwer, 1986; Thompson, 1985; Ayers and Wescott, 1985; Hanson et al., 1993). The use of high leaching rates is essential to prevent the build up of salts in soil and to keep the salinity of percolating moisture as low as possible, and an effective drainage system is generally recommended (Pettygrove and Asano, 1990; Ayers and Wescott, 1985; Hanson et al., 1993). Effluents which have high concentrations of salts would probably best be applied on highly leached soils and on sands where seepage/runoff water will eventually enter water resources which are highly saline (Thompson, 1985). Saline effluents which contain high nitrate concentrations are likely to present the most intractable problems for land application, as the high leaching requirements for saline effluents will result in minimal attenuation of nitrates. Deep-rooted, salt-resistant, fast growing trees such as certain Eucalyptus species should be useful for attenuating nutrients in such effluents, when these are applied to deep, highly leached soils. Examples of two potentially suitable Eucalyptus species are *Eucalyptus grandis* for warmer areas and *Eucalyptus nitens* for colder (frosty) areas of South Africa (Ellis, 1998). Guidelines for irrigating with high-TDS water are contained in manuals that are published by the Department of Water Affairs and Forestry (Department of Water Affairs and Forestry, 1996). These manuals should be consulted for all cases where effluents are discharged to land.

Further measures to help reduce the impact of effluents on groundwater include the following:

(i) Plant suitable crops in vulnerable areas:

- ❑ Maize, sugar cane, certain root crops, fruit trees and certain evergreen tree species are able to utilize nitrogen located as deep down as 2 metres or even deeper. Unused nitrogen near the surface of the soil during the previous growing season will most likely still be located in the root zone the following year, and so not be lost to these plants (Burt and Haycock, 1993).

- ❏ Deep-rooted plants with high water requirements, including most species of evergreen tree (especially Eucalyptus species), help to lower the groundwater table and to keep salts suspended in the vadose zone (Suarez, 1989). Of all vegetation types, woodlands normally have the lowest concentration of N in groundwater (Strebel et al., 1989). In the latter case, woodland trees would probably not include Acacia species, as these trees are known to add nitrates to soil.

- ❏ In arid areas, consider planting crops which require less water.
  For brackish effluents, consider planting salt-resistant crops so that less effluent is required for leaching purposes (Department of Water Affairs and Forestry, 1996).

(ii) Carry out soil and water tests:

Soil tests may be used to ascertain plant-available N in soils, before applying effluent which contains nitrogen. Regular soil moisture monitoring may be carried out to help determine the required modifications to effluent application rates. Annual soil acidity tests may be utilized to determine the quantity of lime or other pH correction agent required to neutralize pH. Test effluent regularly in order to establish optimum irrigation limits. (Department of Water Affairs and Forestry, 1996; U.S. Environmental Protection Agency, 1983).

(iii) Discontinue monoculture practices:

Seasonal crop rotation helps to reduce the potential impact on groundwater of nutrients in effluent (Burt and Haycock, 1993; Canter, 1997; Strebel et al., 1989).

(iv) Reduce tillage depth (Burt and Haycock, 1993; Canter, 1997)

(v) Establish buffer strips:

Trees and shrubs growing in riparian (buffer) zones with shallow water tables reduce nitrogen in groundwater.(Power and Scheepers, 1989). As discussed earlier, Eucalyptus trees are in many cases good candidates for this purpose.

8 IRRIGATION WITH SEWAGE EFFLUENTS: HEALTH PERSPECTIVES

Suitable soils for irrigation by sewage effluent and other pathogenic effluents are clayey soils which contain humus and iron (e.g. dark-red clayey soils):

- ❏ Sorption characteristics of viruses, which are the smallest most mobile pathogens in soil, are similar to those of anionic trace contaminants. Hence soils which have a high percentage of organic carbon, iron oxide and clay are considered suitable for virus sorption. Sorption of viruses by soil media therefore significantly reduces their bioavailability and their leachability. (Pettygrove and Asano, 1990; Canter and Knox, 1986; Oliver et al. 1996).

- ❏ Larger pathogens are rapidly filtered out in clay soils (Pettygrove and Asano, 1990; Shuval et al., 1986; Canter and Knox, 1986).

Suitable crops for irrigation by sewage effluent are placed in three categories, dependent on the treatment received by wastewater (Shuval et al., 1986):

Low risk:

Crops not for human consumption.
Crops heat-processed or dried before human consumption.
Vegetables and fruit for canning.
Fodder crops, harvested and sun-dried before consumption by animals.
Landscape crops (fenced off from public access).

Medium risk:

Pasture grasses and fodder crops.
Crops which do not come into contact with wastewater.
Crops normally eaten only after cooking.
Spray irrigated crops.

High risk:

Other crops not included in the above categories.

Guidelines published by the Department of Health (Department of National Health and Population Development, 1978) should be consulted for information on acceptable sewage treament / land-use categories and other requirements applicable to South Africa.

The following options (**Table 2)** are presented as possible alternatives towards securing measures of health protection for populations who are potentially at risk from the reuse of sewage effluents.

Table 2 Health risk and cost/ management alternatives for populations potentially at risk from the reuse of sewage effluents (after Blumenthal et al., 1989)

Degree of treatment/ application	Treatment type or application details	Degree of health risk	Health risk details	cost/management comparison
(A) Full treatment		least risk		*most expensive
(B) Application methods: - How and when the effluent is applied	applied directly to roots of row crops during safe periods	little risk		* fairly expensive * needs good management
(C1) Partial treatment and crop restriction	conventional secondary treatment	some risk	especially in terms of intestinal infections	* relatively cheap * needs some control
(C2) "	stabilization ponds	full protection		* relatively cheap * needs some control * land requirements
(D1) Partial treatment and human exposure control	conventional treatment	some risk for vegetable consumers little risk for field workers (risk level: dependent on law-abiding society)	bacterial removal insufficient for protection of vegetable consumers	* relatively cheap * need to control/monitor
(D2) "	pond treatment	some risk for vegetable consumers little risk for field workers	bacterial removal insufficient for protection of vegetable consumers	* relatively cheap * need to control/monitor * land requirements
(E1) Partial treatment	conventional treatment	some risk for vegetable consumers some risk for field workers	bacteria and helminth-egg removal insufficient for protection of vegetable consumers helminth-egg removal insufficient for protection of field workers	* relatively cheap
(E2) "	pond treatment	some risk for vegetable consumers low risk for field workers	bacterial removal insufficient for protection of vegetable consumers; sufficient helminth egg removal for field workers	* relatively cheap * land requirements
(F) Restriction on crops and human exposure control	no treatment	very little risk for vegetable consumers some risk for field workers (risk level: dependent on law-abiding society)		* cheap * need to control/monitor
(G)Restriction on crops	no treatment: application to only certain crop-types allowed.	very little risk for vegetable consumers significant risk for field workers		* cheap * need to control/monitor
(H) Human exposure control:	no treatment: protective measures are applicable	reduced risk: risk levels depend on extent of law-abiding society		* cheap * need to control/monitor * ensure: # personal hygiene, # workers wear protective clothing, # food is thoroughly cooked, etc.

Approximate ranking of the alternatives presented in **Table 2** in terms of protection of population health is as follows (after Blumenthal et al., 1989):

(Most Protection)

A	Full treatment (conventional or else waste stabilization ponds with HRT of 25 days or more)
B	Application measures
C2	Partial treatment (pond) + crop restriction
C1	Partial treatment (conventional) + crop restriction
F	Crop restriction + human exposure control
D2	Partial treatment (pond) + human exposure control
D1	Partial treatment (conventional) + human exposure control
E2	Partial treatment (pond)
E1	Partial treatment (conventional)
G	Crop restriction
H	Human exposure control
I	No protective measures

(Least Protection)

NB: Partial treatment (pond): Stabilization pond with 8-10 day HRT.

Additional aspects to consider regarding the above are:

- ❏ Site selection: - Select those sites which have suitable characteristics [for environmental protection, consider factors such as soils, bedrock, slope, buffers, zoning, etc.].
  (Inexpensive, but need to design and plan effectively)

- ❏ Effluent and site management. [e.g. seasonal application requirements, storage facilities, site preparation, etc.]
  (Fairly expensive, manpower training and monitoring needed)

9 SELECTION OF COST-EFFECTIVE SEWAGE TREATMENT AND EFFLUENT TO LAND DISCHARGE FACILITIES

Although there is a wealth of literature addressing the design of sewage treatment systems, very little is available which addresses the relative assessment of different types of sewage treatment system using multiple selection criteria. Most literature relevant to the needs of developing nations addresses the design and performance of oxidation ponds or else compares suitability of oxidation ponds for developing nations in comparison with conventional activated sludge systems. Recently a study was done (Von Sperling, 1996) which compares many different types of sewage treatment system over financial, social, environmental and system performance criteria categories, within the context of suitability for developing nations. The results of this study have been used to develop a potentially useful computer-based decision support tool whose purpose is to help in the selection of suitable sewage treatment system options, given financial, social, environmental and system performance constraints and requirements.

Fifteen commonly used sewage treatment systems in developing countries have been identified by Von Sperling (Von Sperling, 1996). Of these fifteen, twelve have been selected for incorporation into the decision-support system. Three are land application options which in South Africa require sewage to be treated prior to land application and so were not selected as stand-alone systems. One of them, subsurface soil treatment, has been included to form part of a septic tank treatment system. Sufficient information exists on the latter to allow an approximate comparative evaluation with the other options.

The treatment systems considered in this study are:

Facultative Pond
Anaerobic Pond - Facultative Pond
Facultative Aerated Lagoon
Completely Mixed Aerated Lagoon - Sedimentation Lagoon
Conventional Activated Sludge (*continuous flow*)
Extended Aeration (*continuous flow*)
Sequencing Batch Reactors (*intermittent flow*)
Low-rate Trickling Filter
High-rate Trickling Filter
Upflow Anaerobic Sludge Blanket Reactor
Anaerobic Filter
Septic Tank + Subsurface Infiltration

Von Sperling (1996) assessed each treatment system according to nineteen criteria. For the current study, these nineteen criteria were reduced to twelve. Four were excluded either due to very little variation in the range of assessed values or because they were not able to be suitably presented in the computer-based decision support system developed as part of this study (aerosol generation, climate, soils, and influent quantity). Three were incorporated with other similar criteria to form larger categories. (For example, influent quality and influent toxicity were combined because their values were not very different from each other).
Criteria considered in this study are:

Land requirements
Construction costs
Operation and maintenance costs
Operational simplicity
Resistance to influent shock changes in quality (not flow quantity)
BOD reduction requirements
Pathogen reduction requirements
Nutrient reduction requirements
Low sludge generation requirements (for disposal purposes)
Low odour impact likelihood
Low noise impact likelihood
Low insect pest breeding potential

For each criterion, Von Sperling (1996) carried out a comparative evaluation of the treatment systems: The relative suitability of each treatment system was compared with the other systems, using a scale of one "plus" (+: least suitable) to five "plusses" (+++++: most suitable). For some criteria, Von Sperling (1996) also tabulated numeric values (e.g. % reduction for BOD). For the current study, the qualitative evaluations were converted to a numeric scale of one to nine (1,3,5,7,9) and numeric data were adjusted proportionately to fit on a scale from zero to nine (0 - 9). **Table 3** shows the relative values (ratings) assigned to the treatment systems, for each criterion.

In this study, the aim is to rank sewage treatment options from most suitable to least suitable, given the criteria listed above. Firstly this requires, for each criterion, a relative evaluation of treatment options. Secondly it requires a relative evaluation of the criteria. Von Sperling's (1996) ratings apply to the former and not the latter. Doing a relative comparison of criteria is not easy (nor is it reliable) for criteria that are dissimilar. However, it should be possible to do a relative comparison of the importance of criteria for a specific community, or for a specific place. For example, the impact of odours and insects may not be nearly as important as the cost and operational simplicity of a system, to an impoverished rural community. It was decided, therefore, to consider assessing criteria in terms of their importance to a community or within a geographic setting. These "importance weights" need to be evaluated on a site-specific basis.

Decision-support software, whose purpose is to help in the selection of suitable sewage treatment system options from the list of twelve (see above) given the financial, social, environmental and system performance criteria listed above, has been developed as part of this project. For each criterion presented to the computer user, a sliding scale is presented to enable the user to easily select a value from 0 (no importance or not relevant) to 9 (of extreme importance). Once all the values have been entered, the user is presented with a table of entered values for review. The user can then either go back and change some values, or else start the evaluation process. If the latter is done, a graph, a table of values and a simple report are presented.

There is great scope for improvement and extension of the current software. One possibility is to include decision support for defining importance weights.

Table 3:	**Sewage treatment systems: Multiple criteria ratings**												
Treatment Type	Land requirement	Construction cost	Operation and maintenance	Operational simplicity	Influent shock resistance	BOD reduction	Pathogen reduction	Nutrient reduction	Odour reduction	Odour impact	Noise impact	Insect impact	Sludge disposal	Max prodsum
Facultative Pond	1	8	9	9	6	5	5	3	5	5	9	1	9	630
Anaerobic-Facultative Pond	4.4	8	9	9	6	5	5	3	1	1	9	1	9	624.6
Facultative Aerated Pond	9.1	8	6	7	6	5	5	3	7	7	1	5	9	639.9
Fully Aerated Pond	9.2	8	5	5	6	5	5	3	5	5	1	1	5	523.8
Activated Sludge	9.4	1	3	1	4	7	3	5	7	7	1	7	1	444.6
Extended Aeration	9.4	4	1	5	6	9	3	5	9	9	1	7	3	561.6
Sequencing Batch Reactor	9.4	3.5	2	7	6	7	3	5	5	5	1	7	2	521.1
Low Rate Trickling Filter	8.7	3	6	5	3	7	3	5	7	7	7	1	3	528.3
High Rate Trickling Filter	9.1	4.5	6	5	5	7	3	4	7	7	7	5	1	572.4
Upflow Anaerobic Sludge Blanket	9.8	7	9	7	3	5	3	1	3	3	9	7	7	637.2
Septic Tank - Anaerobic Filter	9.3	4.5	9	7	4	5	3	1	3	3	9	7	7	619.2
Septic Tank and Subsurface infiltration	3	7	9	7	6	8	6	5	4	4	9	6	8	702

10 EXPERT SYSTEMS-BASED DECISION SUPPORT TOOLS

Effluent to land decision-support software

The effluent to land decision support software consists of several components which are designed with two purposes in mind:

- to be used as decision aids sequentially in an effluent permitting study,
- to be used as separate tools for site identification, crop selection, irrigation area size estimation, contaminated runoff storage size estimation, assimilation capacity estimation of site soils, and more.

The software should be seen as being fit for demonstration purposes only, for the following reasons:

- The software still needs to be validated.
- On some computers, some buttons in the health regulatory tool (those buttons which enable the user to return to the main menu) become inactive once the report is generated (this is a "bug").
- The results of some components such as the water balance tool need added interpretive capabilities.
- Except for the health permitting tool and part of the contaminant limits assessment tool, the software is not tied to regulations relevant to effluent irrigation in South Africa. If and when such regulations exist, the software could be readily modified so as to support them.

Components of the software

The software tools and their uses are described hereunder:

- Health permitting tool for sewage effluent

  Given a sewage treatment stage and a proposed land-use application, this component specifies whether it is permissible to apply the effluent for the land use in question or not, and if permissible, it identifies those measures that need to be implemented from a human health protection standpoint. This tool implements the Department of Health guidelines referred to earlier in this report (Department of National Health and Population Development, 1978).

- A site-assessment advisor for sewage effluent, which may also have applicability for organic effluents

Given the treatment stage of sewage effluent, this component helps determine whether site-specific factors such as soil pH, site slope, depth to groundwater, distance to surface water and distance to residences are likely to cause problems. If so, suitable mitigatory measures are presented.

❏ Soil contaminant limits assessment component

This component presents a simple table which shows what the current trace element concentration limits are for South African soils, and given the trace element concentrations from a soils analysis, it determines what trace element limits are exceeded, and by how much, and indicates whether effluent may be applied to the site in question, or not. If at least one trace element limit is exceeded, and the effluent contains that trace element, the site is not considered suitable for effluent application.

❏ Monthly precipitation evaporation assessment tool

This component is designed to help determine the capacity of an area of land to accept non-saline effluent on a monthly basis, taking into account monthly precipitation evaporation, effluent irrigation area and contaminated runoff storage volume data.

The component uses a table on a form for both input data and output data. Input data requirements are monthly precipitation, leaching factor, crop factor, potential evaporation, the area available for effluent irrigation, and the volume of effluent to be disposed of. Leaching factor (LF) is the proportion of total moisture applied to the land surface which percolates through the soil until it is out of reach of plant roots and where capillary forrces cannot bring the moisture back towards the surface. Crop factor (CF) is the ratio of potential evapotranspiration of the crop and ground surface to potential evaporation from an equivalent area of open water.

Output data for each month addresses excess runoff (if any), the runoff storage capacity required, and the extra area required for effluent irrigation (when there is potential to make use of extra land). For each month, it is assumed that the applied moisture (including both precipitation and irrigation) will either evapotranspire (direct evaporation from the ground and transpiration through plants), percolate through the ground, or run off the site. It is assumed that evapotranspiration and percolation will take precedence over surface runoff. Thus:

- If potential evapotranspiration and the depth of liquid percolating through the soil for the month are **greater than** the depth of liquid from precipitation and irrigation, it is assumed that there will be no runoff, and that the shortfall will be made up by irrigating with contaminated runoff kept in storage.

- If potential evapotranspiration and depth of liquid percolating through the soil for the month are **less than** the depth of liquid from precipitation and irrigation, it is assumed that there will be runoff, and that this runoff will be collected in storage.

- If potential evapotranspiration and depth of liquid percolating through the soil over the month is **less than** the depth of liquid from precipitation only, it is assumed there will be runoff. If no effluent is applied during the month, it is assumed this runoff will not be collected in storage.

Note: The terms "potential evapotranspiration" and "estimated crop water requirement" may be considered to mean the same thing, assuming that crops cover the entire irrigation area. Potential evapotranspiration may be estimated by multiplying potential evaporation (data derived from a Class A pan) by the crop factor. (Van Eeden, 1998).

Excess contaminated runoff is stored on a month-by-month basis and is utilized when there is spare evapotranspirative capacity for any month.

Output data not only includes the monthly data mentioned earlier, it also includes an estimated design storage capacity which will be sufficient to cope with runoff storage requirements for one year, as well as a warning that effluent is being applied for a month when precipitation is greater than potential evapotranspiration plus moisture lost to percolation (if this warning is relevant). The leaching fraction (LF) is the proportion of applied moisture which percolates beyond the root zone. LF may theoretically range from 0 to 1, but usually lies in the range 0,05 to 0,2.
As this tool does not address daily data values, the results should be used as **rough guideline** values, only.

❏ Effluent application-rate tool

This component presents columns on an electronic form. Similar to the one for soils, it utilizes annual trace element application rate limits:

> These limits are based on the current trace element limits for sludge application rates in South Africa (WRC, 1997). The effluent application rate limits could have been derived from an assumption such as: "Given that it takes 25 years of effluent application to increase trace element concentrations in soil to those specified in the soil limits, what would the annual application rate for each trace element then be ? " (WHO, 1995; Smith, 1996). This is the approach recommended for sludge by the World Health Organization (WHO, 1995). For effluents, such an approach could result in significant errors for reasons mentioned earlier in this report. Further research is needed regarding this aspect, therefore the land-application rate limits presented in the table need to be used with caution.

Given a required effluent application rate to land and a chemical analysis of contaminant concentrations in the effluent, the application rate of individual contaminants to land is calculated and compared with the specified limits. If any is at or above the prescribed limit, the application rate is considered to be too high. The user is presented with the maximum annual effluent application rate, as volume and liquid depth, which could be used to comply with these limits. The user is then able to revize the required annual effluent application rate so that it is equal to or less than this amount.

The annual nitrogen application rate is calculated at the same time as the trace element application rates are. The nitrogen supplied by the effluent is displayed so that a comparison can be made with annual crop nitrogen requirements for a variety of crops. The crop nitrogen requirements should preferably equal or exceed that supplied by the effluent. If not, the effluent application rate may need to be reduced. It is important that the crops grown should make as much use of the nitrogen supplied by the effluent as possible, taking into account the seasonal variability of crop nitrogen needs and the nitrogen application rate.

The annual effluent application rate limit derived from this component needs to be compared with that derived from the water balance component. The most conservative application rate limit is the one that should normally be accepted for further consideration in a permit exemption study. Probably the most serious limit is the one assigned by the trace element application rate component. If the other limits happen to be more conservative, there are measures which can be readily applied in order to allow higher application rates.

❏ Crop selection assistant for crops (addresses crop sensitivity to TDS, Cl and B)

High levels of TDS (salinity), chlorides(Cl) and boron (B) are often encountered in effluent used for irrigation. Crops are sensitive to high concentrations of each of these constituents, but they have different degrees of sensitivity depending on the crop type and constituent of concern.

Given a concentration range for each constituent in an effluent, the crop selection assistant uses a filtering process to exclude sensitive crops from the list of crops being considered (see examples of crop sensitivity categories regarding chloride and boron concentrations in **Table 4** and **Table 6** in the appendix).

Chemical concentration ranges of the effluent are selected by clicking on one of the slots showing 'Salinity', 'Boron', or 'Chloride'. The concentration level categories are presented for each one selected. A range must then be selected using the mouse. The system responds by displaying in one column crops which are not sufficiently tolerant to the concentration range of the substance in question, and displaying in another column those crops which are.
The "Filter" button needs to be “clicked” on to see the subset of crops which have sufficient tolerance for all three substances at the concentration ranges selected.

In general, the higher the concentrations, the fewer crops will be suitable.

Note: This software does not address crops which are sensitive to very low concentrations of boron.

❏ Sewage-effluent health-risk versus cost comparative assessor

This is an expert system which provides information on population health risk and simple treatment/irrigation control options, given -

(a) how costly the sewage treatment is/will be;
(b) the expected level of effective site management;
(c) the extent to which field workers' activities will be monitored and controlled.

Four options are given for the question: "How expensive may the treatment/ land application option be ?". Only one may be chosen. The following questions are then asked, with the number of options given:

What degree of management and monitoring is to be applied at the effluent irrigation site ?
(Three options are given from which one may be chosen.)

What degree of monitoring of irrigation site activities is to be carried out ? (Three options are given from which one may be chosen.)

What level of control over irrigation site activities is to be exercised ?
(Three options are given from which one may be chosen.)

An example of results are as follows:

SEWAGE TREATMENT/IRRIGATION OPTION AND HEALTH RISK RESULTS

1.
Assuming funds to cover a relatively cheap cost option are available, the following treatment option is possible:

Minimum sewage treatment required:
(1) Partial sewage treatment (oxidation ponds).

Effluent application:
(2) No irrigation restrictions considered.

Degree of risk:
(3) Little risk for field workers.
(4) Some risk for raw vegetable consumers, as bacterial and helminth removal will be insufficient for protection.

2.
Assuming funds to cover a relatively cheap cost option are available, the following treatment option is possible:

Minimum sewage treatment required:
(1) Partial sewage treatment (conventional secondary treatment).

Effluent application:
(2) No irrigation restrictions considered.

Degree of risk:
(3) Some risk to field workers, as bacterial and helminth removal will be insufficient for their protection.
(4) Some risk to raw vegetable consumers, as bacterial and helminth removal will be insufficient for their protection.

3.
Assuming funds to cover a relatively cheap option are available, and that there will be some monitoring, control and management exercised over effluent irrigation, the following option appears suitable:

Minimum sewage treatment required:
(1) Partial sewage treatment (oxidation pond or conventional secondary treatment).

Effluent application:
(2) There must be control to prevent exposure of field workers to effluent in terms of ingestion, spray inhalation and skin contact with the effluent.

Degree of risk:
(3) Little risk to field workers.
(4) Some risk to raw vegetable consumers, as bacterial removal will be insufficient for protection of raw vegetable consumers.

4.
Assuming funds to cover a relatively cheap option are available, and that the types of crop grown will be strictly controlled, the following option appears suitable:

Sewage treatment required:
(1) Partial sewage treatment (oxidation ponds).

Effluent application:
(2) Effluent must be restricted to crops not eaten raw.

Degree of risk:
(3) Minimum risk to field workers.
(4) Minimum risk to vegetable consumers.

5.
Assuming funds to cover a relatively cheap option are available, and that there will be some control exercised over effluent irrigation, the following option appears suitable:

Sewage treatment required:
(1) Partial sewage treatment (conventional secondary treatment).

Effluent application:
(2) Effluent must be restricted to crops not eaten raw.
(3) Effluent should only be applied during safe periods.

Degree of risk:
(4) Some risk to field workers, especially in terms of intestinal infections.
(5) Low risk to raw vegetable consumers.

❏ Sewage treatment system option selection assistant

This software's purpose is to help in the selection of suitable sewage treatment process options from a list of twelve, given financial, social, environmental and system performance criteria (listed below). For each criterion presented to the computer user, a sliding scale is presented to enable the user to easily select a value from 0 (no importance or not relevant) to 9 (of extreme importance). Once all the values have been entered, the user is presented with a table of entered values for review. The user can then either go back and change some values, or else start the evaluation process by clicking on a button on the screen. If the latter is done, a graph, a table of values, a simple report and a list of pros and cons of each treatment option are presented.

The graph shows the treatment options ordered according to increasing suitability, and whose magnitude indicates their relative suitability.

Sewage treatment process options available for selection are:
Facultative pond, anaerobic facultative pond, facultative aerated pond, fully aerated pond, activated sludge, extended aeration, sequencing batch reactor, low-rate trickling filter, high-rate trickling filter, upflow anaerobic sludge blanket, septic tank - anaerobic filter, and finally, septic tank - subsurface infiltration.

Selection criteria used to rank sewage process options in terms of likely suitability are:
Land restrictions, capital cost restrictions, operating cost restrictions, requirements for operational simplicity, requirements for influent shock resistance, BOD reduction requirements, pathogen reduction requirements, nutrient reduction requirements, odour reduction requirements, low noise impact requirements, low insect impact requirements, and low sludge production requirements.

Although the software is functional, there is significant scope for extending it and adding extra functionality.

11 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

11.1 Summary

South Africa faces major problems in disposing of its liquid and solid wastes in an environmentally sustainable manner, as its waste production is exponentially increasing and costs are also increasing per unit mass of waste to be disposed of in an environmentally sustainable way. Being a semi-arid country, South Africa is facing a further problem regarding severe limits on available, good-quality water resources.

Hence the major problems are:

(i) Ever-increasing waste production volumes with increasing costs of treatment and disposal present significant implications for our economy.

(ii) Water is a scarce resource. As the demand outstrips supply, this forces up the cost of water and imposes more severe restrictions on water use.

(iii) Water pollution has become an ever-increasing threat to our economy, quality of life and environment.

It is believed that South Africa needs to utilize effluents in such a way that wastewater is used for non-potable purposes (such as for agriculture) in place of fresh water, and that the latter water is reserved for potable and recreational use. As effluent producers are likely to want to reduce effluent volumes needing to be disposed of by evaporating as much of it as possible, it is also believed that a regulatory mechanism is needed to ensure that excessive amounts of moisture from effluent are not irretrievably lost to the atmosphere. It is important that crops and soil be selected primarily on their capacity to effectively treat non-saline effluents, and that effluent then be applied at a rate not greater than that which matches this capacity. Land application of effluents requires wise management and control in order to:

❏ minimize health risk to field workers and crop consumers,

❏ minimize pollution risk to water resources,

❏ minimize needless water losses to the atmosphere,

❏ minimize the impact on the environment (e.g. ecological impact; odour impact), and

❏ maximize the benefits in terms of crops grown; cost savings over alternative forms of treatment; availability of higher quality source water for alternative use; etc.

There are several options to consider when applying effluent to land: to **supply crop nutrient** requirements; to **supply crop water** requirements or to **treat the effluent** by employing the filtering capabilities and chemical attenuation characteristics of soil and vegetation. A further option, **disposal of effluent** to land, should preferably be the last option made available to effluent producers, and where practised, it needs to be done without an unacceptable negative impact occurring on human health, water resources or the environment. In most countries, the major objective of effluent to land applications is the disposal of effluent at minimal cost/impact to (a) the effluent generator, (b) human health, and (c) the receiving environment. Guidelines therefore need to address the issues of crop nutrient and water requirements, on-land effluent treatment options and the impact of effluent application to land on human health and on the receiving environment.

The need for guidelines for effluent application to land is becoming more acute, and as these guidelines are necessarily complex, there is believed to be a need for such guidelines to be incorporated in user-friendly software. Software which supplies tools to help in guideline interpretation and implementation, together with some form of routine "intelligence" is believed to be important, as users are likely not to have all the expertise required to interpret and implement the guidelines. The development of expert systems-based software is believed to be a way to achieve this. The overall objective of this project is to develop expert systems incorporating guidelines and advice on land-based effluent disposal and effluent use, together with the relevant decision-making processes, in order to provide decision-makers with appropriate, readily accessible information and expertise on personal computers.

Prior to development of the software, suitable guidelines and advice needed to be identified. The following issues were therefore first addressed in the study:

- ❏ Characterization of effluents and soils for land application and crop irrigation purposes.

- ❏ Identification of suitable crop types, soil characteristics and design/planning/management aspects in terms of land application of effluent.

- ❏ Identification of limiting parameters and related algorithms that help determine the maximum application rates of effluent in terms of major effluent constituents.

- ❏ Given the objective: to dispose of as much effluent as possible over a limited land area with minimal impact on the environment, the following aspects were onsidered:
  - i) crop nutrient requirements,
  - ii) crop water requirements,
  - iii) use of vegetation and soils to treat effluent water to an acceptable standard.

- ❏ Management options which effectively reduce the risk of contamination of water resources or else enable more effluent to be applied to a restricted land area.

- ❏ Identification of suitable sewage treatment system options in terms of various criteria, one of the aims being the production of effluent suitable for land application.

11.2 Conclusions

Important results from the study include the following:

- ❏ Effluents with a high pathogen content require certain treatment stages and controls on crop irrigation practices to be specified, together with proper monitoring, in order to effectively limit the risk to human health.

- ❏ Effluents with significant quantities of potentially toxic trace elements need to be restricted in terms of levels of contaminant build-up in site soils as well as in terms of annual application rates. This would be in order to protect human, animal and plant health via different food-chain pathways.

- ❏ Effluents with high nutrient concentrations need to be restricted in terms of the amount that can be applied to land in terms of what crops need, and soil liming may be required to counteract the effects of soil acidification by nitrogenous effluents, in order to effectively reduce the pollution risk to water resources.

- ❏ Effluents with significant concentrations of macro elements (e.g. TDS, Cl, B, Na) need to be applied to those crops and soils which are relatively insensitive to such concentrations, and sophisticated irrigation and soil management may need to be carried out to minimize the impact of those macro-elements on crops and soils.

- ❏ Effluents with a high concentration of biodegradable organics ("high COD effluents") need to be applied to land with consideration for impacts in terms of pathogen growth, odour generation, insect breeding and soil acidification. Further, the likely effects of bacterial slime layers on reduced soil permeability and the impact of anoxic conditions in soil on plant root health may require that artificial drainage and wetting/drying cycles be instituted.

- ❏ Effluents which are acidic or alkaline, and those which contain high concentrations of suspended solids, detergents and grease generally may need to be specially treated prior to land application. Acidic or alkaline effluents are likely to re-mobilize ionic contaminants sorped to soil particles. Effluents which contain high concentrations of suspended solids, or oils and greases, can clog soil pores at the soil surface, thus preventing irrigated effluent from percolating down into the soil, and also causing plant roots to suffocate from lack of oxygen. Detergents can remobilize contaminants in the soil, carrying them down to groundwater. High-sodium, low TDS effluents can cause clogging in soils containing clay.

- ❏ Soils need to be suitably characterized in order to help describe the potential ability of soils to attenuate contaminants in effluent, given a few key soil characteristics. The following comments are relevant:

    The overriding factor which influences the mobility or bioavailability of ionic contaminants in soil is pH, where low pH mobilizes cationic contaminants and high pH mobilizes anionic contaminants in a soil solution. Secondary factors are the soil media type, where organic carbon, non-kaolinitic/kaolinitic clays, iron/ manganese oxides/oxy-hydroxides and carbonate soils are most effective in attenuating cationic contaminants in low and neutral pH conditions, and to a lesser extent in attenuating anionic contaminants in neutral to high pH conditions. Organic carbon is most effective in attenuating certain heavy metals and non-volatile organic chemicals.

Effluents which contain high levels of pathogens, such as partially treated sewage effluents, are probably best applied to clay soils which contain humus and iron (e.g. dark red clayey soils).

> The sorption characteristics of viruses, which are the smallest, most mobile pathogens in soil, are similar to those of anionic trace contaminants. Hence soils which have a high percentage of organic carbon, iron oxide and clay are considered suitable for virus sorption. Sorption of viruses by soil media therefore significantly reduces their bioavailability and their leachability. Larger pathogens are rapidly filtered out in clayey soils.

- ❏ The more mobile a contaminant is, the more it presents a risk in terms of groundwater contamination. On the other hand, the less mobile a contaminant is, the more the likelihood of build-up of contaminant concentrations in the soil surface to levels which could represent an unacceptable risk factor to plants, animals and humans (for the latter two, this would be from eating plants or ingesting soil). However, the risk implied in the latter is likely to be small when considering agronomic applications.

- ❏ As most potentially toxic inorganic contaminants are heavy metals (cations), it is recommended that soils be tested for cation exchange capacity prior to determining what contaminant application rate limits are applicable. It is recommended that for heavy-metal contaminants and for soils with a CEC of less than 5 meq/100g, conservative limits that are normally defined for non-calcareous sands should be used. For soils with a CEC of between 5 and 15 meq/100g, use limits which are double the most conservative limits, or preferably use the following equation:

  New limit = (most conservative limit) * (CEC - 1)/4

  For soils with a CEC greater than 15, use limits which are four times greater than the most conservative limits. (U.S. Environmental Protection Agency, 1992).

11.3 Recommendations

Land application of sewage and other organic/ pathogenic effluents for beneficial purposes should enjoy high priority in South Africa, as:

- ❏ research shows that soils are amongst the most effective means of treating such effluents;

- ❏ crop irrigation allows the nutrients in effluent to be recycled, thus reducing the need for added fertilizers for crops and, where no fertilizers are added, crop irrigation reduces the potential impact of such nutrients on water resources;

- ❏ irrigation with effluents in place of higher quality source water frees the latter for alternative use.

Along with the above comes the need to ensure that proper mitigation measures are in place, land application and drainage facilities are properly installed, the sites are properly managed, and that the environmental impact of such activities has been assessed and accounted for. In order to carry out the above, not only are restrictions needed in terms of effluent type/ treatment stage and land-use category, but also restrictions in terms of effluent type/ treatment stage and each of the following:

- ❏ allowable site parameters (slope, depth to groundwater, etc.),
- ❏ suitable soil characteristics, and
- ❏ allowable maximum effluent application rates.

Together with the above comes the need for the development and institution of suitable procedures designed to:

- ❏ control the activities of effluent producers, and
- ❏ help effluent producers to manage their effluents in an environmentally sustainable, yet affordable way.

These procedures are necessarily complex, so there is a need to have available suitable decision support tools for both administrators and site managers. Software tools could be in the form of "intelligent advisors", geographic information systems, database systems, "web-based" communication tools and more. The expert systems-based software developed for this project, once modified, expanded and validated, should provide the required administrative advisory system. Suitable links from this software to GIS systems, databases and the Web could also be established. (There are active links to dBase tables in the current software.)

Other recommendations relating to this project:

> It is recommended that further research be carried out on the bioavailability and mobility of priority contaminants in effluent applied to land, with the aim of determining realistic limits in terms of contaminant mobility and distance to a water resource, soil attenuation, crop and animal uptake, the toxic nature of a contaminant, and limiting pathways, amongst others. The limits to be defined should relate to contaminant concentration in effluent, concentration levels in irrigated soils and to annual land application rates. Research efforts should be aimed at high-priority contaminants which are likely to be found in effluents such as treated sewage effluents and rural industrial effluents.
>
> Presentation of papers at symposia or in journals is recommended for technology transfer purposes. Demonstration of software at workshops, as well as via the WRC's website, is recommended for educational and validation purposes.

12 REFERENCES

Abbott S, 1996 *Pers. Comm.*, Shane Abbott, Forestek, CSIR, Nelspruit.

Allen H, 1997 *Pers. Comm.* Visiting lecture given on 8th July 1997 at CSIR, Stellenbosch. Department of Civil and Environmental Engineering, University of Delaware, Newark, Delaware.

Aller L, Bennett, T, Lehr, J H, Petty, R J, 1987 DRASTIC: A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings. US EPA Report No. EPA/600/2.87/035.

Adriano D C**,** 1986 *Trace Elements in the Terrestrial Environment.* Springer, New York.

Adriano D C, (Ed) 1991 *Water, Air and Soil Pollution.* Kluwer Academic Publishers, Dordrecht.

Ayers R S and Wescott D W, 1985 *Water Quality for Agriculture.* FAO, Rome. FAO Irrigation and Drainage Paper No: 29.

Benjamin M M, Sletten R S, Bailey R P and Bennet T, 1996 Sorption and Filtration of Metals using Iron-Oxide-Coated Sand. *Wat. Res*, 30 (11) pp 2609 - 2620.

Blumenthal U, Strauss M, Mara D D and Cairncross S, 1989 Generalized Model of the Effect of Different Control Meaures in Reducing Health Risks from Waste Reuse, *Wat. Pollut. Res. Contr.*, 21 (6/7) pp 567 - 578.

Bouwer H, 1985 Renovation of wastewater with rapid-infiltration land treatment systems. In: Asano, T (Ed.), *Artificial recharge of groundwater,* Butterworth, Massachusetts.

Broadbent F E and Reisenauer H M**,** 1990 Fate of Wastewater Constituents in Soil and Groundwater: Nitrogen and Phosphorus. In Pettygrove and Asano (Eds.): *Irrigation with Reclaimed Municipal Wastewater - A Guidance Manual*, Lewis, Mi.

Burt T P and Haycock N E, 1993 Controlling Losses of Nitrate by Changing Land Use. In Burt T P, Heathwaite A L and Trudgill S T (Eds): *Nitrate: Processes, Patterns and Management,* Wiley, Singapore.

Canter LW, 1997 *Nitrates in Groundwater*, CRC Press, Boca Raton, Fla..

Canter L W and Knox R C, 1986 *Septic Tank System Effects on Ground Water Quality.* Lewis, Michigan..

Chaney R L, 1990(a) *Twenty Years of Land-Application Research*, BioCycle, 31 (9) pp 54-59.

Chaney RL, 1990(b) *Twenty Years of Land-Application Research*, BioCycle, 31 (10) pp 68-73.

CSIR, 1991 The Situation of Waste Management and Pollution Control in South Africa, Report for the Department of Environment Affairs, Pretoria

Department of National Health and Population Development, 1978 *Guide: Permissible Utilization and Disposal of Treated Sewage Effluent*. Department of National Health and Population Development, Pretoria.

Department of Water Affairs and Forestry, 1993 *S.A. Water Quality Guidelines* series. 1st Ed, 4: Agricultural Use, Pretoria.

Department of Water Affairs and Forestry, 1996 *S.A. Water Quality Guidelines* series. 2nd Ed., 4: Agricultural Use, Pretoria.

Domenico P A and Schwartz F W, 1990 *Physical and Chemical Hydrogeology*. John Wiley and Sons, Singapore.

Ekama G A, 1993a *Some Background to the Sludge Management Situation in South Africa.* In Ekama, G.A. (Ed): *Sewage Sludge Utilization and Disposal,* Water Institute of Southern Africa.

Ekama G A, 1993b *Sludge Management for Land Disposal.* In Ekama, G.A. (Ed): *Sewage Sludge Utilization and Disposal*, Water Institute of Southern Africa.

Ekama GA, 1995 Pers. Comm.. Civil Engineering Faculty, University of Cape Town.

Ellis F, 1998 Pers. Comm., Forestry Department, University of Stellenbosch.

Fey M V, 1990 *Land Treatment of Hazardous Wastes.* In *Survey of Hazardous Waste Technology,* Report for Foundation for Research Development, Pretoria.

Fuller W H, 1978. Investigation of Landfill Leachate Pollution Attenuation by Soils, EPA 600/2-78-158, U.S. Environmental Protection Agency , Cincinnati, Ohio.

Foster S S D, 1987 Fundamental Concepts in Aquifer Vulnerability, Pollution Risk and Protection Strategy. In Van Duijvenbooden W and Van Waegeningh H G, (Eds) 1987 *Vulnerability of Soil and Groundwater to Pollutants, Proceedings of the International Conference on March 30 - April 3, 1987 at Noordwijk Aan Zee,* TNO Committee on Hydrological Research, rivm, The Hague, Netherlands.

Hanson B, Grattan SR and Fukton A, 1993 *Agricultural Salinity and Drainage*, Davis, California.

Hespanhol I, 1990 Guidelines and Integrated Measures for Public Health Protection in Agricultural Reuse Systems, *J. Wat. Sanit. Res. Tech. - Aqua*, 39 (4), pp 237 - 249.

Idema G K and Rodda N, 1994 *Reuse of Wastewater - An Updated Literature Survey,* WATERTEK, CSIR, Proj. No: 27748 6800 6870 File No: W 9/7/1.

Kempster P L and Smith R, 1985 Proposed aesthetic/physical and inorganic drinking-water criteria for the Republic of South Africa. CISR Report No 628.

Khouri N, Kalbermatten J M and Bartone CR, 1994 *Reuse of Wastewater in Agriculture: A Guide for Planners*, Water and Sanitation Report No. 6, World Bank Water and Sanitation Programme, Washington.

Korentajer L, 1991 A Review of the Agricultural Use of Sewage Sludge: Benefits and Potential Hazards, *Water SA*, 17 (3), pp 189-196.

Lerner D, 1996 *Organic Pollution of Groundwater.* Course Notes, University of Bradford, U.K.

Ministry of Agriculture, Fisheries and Food, 1991 *Code of Good Agricultural Practice for the Protection of Water*. U.K.

McConkey G, 1997 Pers.Comm. Department of Water Affairs and Forestry, Cape Town.

Metcalf & Eddy Inc., 1991 *Wastewater Engineering: Treatment Disposal Reuse.* McGraw-Hill, San Francisco

Misstofvereniging van Suid-Afrika, 1994 *Bemestingshandleiding van Suid Africa*. - 3rd Publication. - Lynwoodrif. Pretoria, 298 p.

Oliver Y M, Gerritse R G, Dillon P J and Smettem K R J, 1996 Fate and mobility of stormwater and wastewater contaminants in aquifers. 1. Literature review. Centre for Groundwater Studies, Australia. Report No. 67, 32p.

Page A L and Chang A C, 1990 Fate of Wastewater Constituents in Soil and Groundwater: Trace Elements. In Pettygrove and Asano (Eds.): *Irrigation with Reclaimed Municipal Wastewater - A Guidance Manual*, Lewis, Mi.

Pescod M B and Arar A, 1985 *Treatment and Use of Sewage Effluent for Irrigation.* Butterworths, London

Pettygrove G S and Asano T, (Eds), 1990 *Irrigation with Reclaimed Municipal Wastewater.* Lewis, Chelsea, MI.

Power J F and Scheepers J S, 1989 Nitrate Contamination of Groundwater in North America, *Agricultural Ecosystems & Environment* 26 (3 & 4).

Poynton R J, 1984 *Characteristics and Uses of Selected Trees and Shrubs*. Directorate of Forestry, Pretoria..

Shuval H I, Adin A, Fattal B, Rawitz E and Yekutiel P, 1986 *Wastewater Irrigation in Developing Countries.* World Bank Technical Paper No. 51.

Sililo OTN, Conrad JE, Murphy KOH, Tredoux G, Eigenhuis B, Ferguson MCD and Moolman H, 1999 *Investigation of the Contaminant Attenuation Characteristics of the Soil Aquifer System with Special Emphasis on the Vadose Zone*, Water Research Commission, Pretoria. WRC Report No. 572/1/99)

Smith S R, 1996 *Agricultural Recycling of Sewage Sludge and the Environment.* CAB International, Wallingford.

Suarez D L, 1989 Impact of Agricultural Practices on Groundwater Salinity, Agricultural Ecosystems & Environment, 26 (3-4), pp 215-228

Strebel O, Duynisveld W H M and Bottcher J, 1989 Nitrate Pollution of Groundwater in Western Europe, *Agriculture, Ecosystems and Environment,* 26 (3-4), pp 189-214.

Tanji K and Valoppi L, 1989 *Groundwater Contamination by Trace Elements.* In Bouwer H. and Bowman R S (Eds.): *Effects of Agriculture on Groundwater,* Special Edition of Journal: Agriculture, Ecosystems and Environment, 26, Elsevier, Amsterdam.

Thompson J G, 1985 *Guidelines for the disposal of Effluent on Land in South Africa.* Information Bulletin series: Soil, SIRI: Dept. Of Agriculture, Pretoria.

U.S. Environmental Protection Agency, 1992 *Guidelines for Water Reuse.* Washington, DC., Ref.: EPA/625/R92/-004

Van Eeden F J, 1998 *Written Comm.,* Directorate: Agricultural Resource Conservation, Durbanville, dated 31st August.

Von Sperling M,. 1996 Comparison Among the Most Frequently Used Systems for Wastewater Treatment in Developing Countries, *Wat. Sci. Tech.* 33, (3), pp 59 - 72.

WHO, 1994 Health, Agricultural and Environmental Aspects of Wastewater and Excreta Use, WHO/FAO/UNEP/UNCHS Workshop, Harare, Zimbabwe. Rep.No: WHO/EOS/95.3

WHO, 1995 *Developing Human Health-Related Chemical Guidelines for Reclaimed Wastewater and Sewage Sludge Applications in Agriculture.* World Health Organization, Geneva.

WRC, 1997 *Permissible Utilization and Disposal of Sewage Sludge*, Edition 1, Department of Agriculture, Department of Health, Department of Water Affairs and Forestry, WRC and WISA, Pretoria, WRC Report No. TT 85/97.

13 APPENDIX

Table 4: Crops grouped according to chloride tolerance. (According to threshold chloride concentrations in saturated-soil extracts (mmol/ℓ). (Department of Water Affairs and Forestry, 1996)

Sensitive (10 mmol/ℓ)	Moderately sensitive (15 mmol/ℓ)	Moderately tolerant (20 - 35 mmol/ℓ)	Tolerant (40 - 60 mmol/ℓ)	Very tolerant (70 - 80 mmol/ℓ)
Strawberry	Pepper	Trefoil, big	Beet, red	Sorghum
Bean	Clover, strawberry	Lovegrass	Fescue, tall	Bermuda grass
Onion	Clover, red	Spinach	Squash, zucchini	Sugar beet*
Carrot	Clover, alsike	Alfalfa	Harding grass	Wheat grass, fairway crested
Radish	Clover, ladino	Sesbania*	Cowpea	Cotton
Lettuce	Corn	Cucumber	Trefoil, narrow-leaf bird's foot	Wheat grass, tall
Turnip	Flax	Tomato	Ryegrass, perennial	Barley*
	Potato	Broccoli	Wheat, Durum	
	Sweet potato	Squash, scallop	Barley (forage)*	
	Broad bean	Vetch, common	Wheat	
	Cabbage	Wild rye, beardless		
	Foxtail, meadow	Sudan grass		
	Celery	Wheat grass, standard crested		
	Clover, Berseem			
	Orchards grass			
	Sugarcane			

* Less tolerant during emergence and seedling stage

** Multiply the mmol/ℓ chloride concentration by 35.5 to convert to the concentration in mg/ℓ.
Crops listed in order of increasing tolerance from top to bottom.

Table 5: Relative susceptibility of crops to foliar injury from saline sprinkling waters (Department of Water Affairs and Forestry, 1996).*

Chloride concentration (mg/ℓ) causing foliar injury***			
<175	**175-350**	**350 - 700**	**>700**
Almond	Pepper	Barley	Cauliflower
Apricot	Potato	Maize	Cotton
Citrus	Tomato	Cucumber	Sugar beet
Plum		Lucerne	Sunflower
Grape **		Safflower	
		Sesame	
		Sorghum	

* Susceptibility based on direct accumulation of salts through the leaves

** On borderline with next category

*** Foliar injury is influenced by environmental conditions. These data are presented only as general guidelines for daytime sprinkling, under conditions which are neither too hot nor too dry.

Table 6: Boron tolerance threshold values for agricultural crops, soil water basis (after Ayers and Wescott, 1985)

Sensitivity	Crop	Threshold Concentration (mg/ℓ)
Very sensitive	Lemon, blackberries	0.3 - 0.5
Sensitive	Deciduous fruit trees, citrus (orange, grapefruit), avocado, grape and onion, barley, bean, sweet potato	0.5 - 0.75
Moderately sensitive	Sesame, strawberry, beans, peanut, sunflower and wheat	0.75 - 1.0
Between moderately sensitive and moderately tolerant	Carrot, pepper, pea, potato and radish	1.0 - 2.0
Moderately tolerant	Lettuce, cabbage, celery, cucumber, turnip, oats, corn, clover, mustard, squash and muskmelon	2.0 - 4.0
Tolerant	Milo, tomato, parsley, vetch, red beet, alfalfa and sugar beet	4.0 - 6.0
Very tolerant	Cotton	6.0 - 10.0
Highly tolerant	Asparagus	10.0 - 15.0

Table 7: Guideline - Trace elements in irrigation water (Department of Water Affairs and Forestry, 1996)

Max. Limit (mg/ℓ) *	**Effects****
20	**Aluminium (Al)** One of the macro soil constituents. Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils (pH > 7.0) will precipitate the ion and eliminate toxicity.
2	**Arsenic (As)** Toxicity to plants in nutrient solutions varies widely, ranging from 12 mg/ℓ for Sudan grass to less than 0.05 mg/ℓ for rice. With the exception of root crops, crop growth is usually retarded before accumulation dangerous to consumers can occur.
0.5	**Beryllium (Be)** Toxicity to plants in nutrient solutions varies widely, ranging from 5 mg/ℓ for kale to 0.5 mg/ℓ for bush beans.
0.05	**Cadmium (Cd)** Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/ℓ in nutrient solutions. Conservative limits are recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
1	**Chromium (Cr)** Toxicity in nutrient solutions has been observed at a concentration of 0.5 mg/ℓ. Not generally recognized as an essential growth element. Toxicity depends on its oxidation state in water and soil and on soil reactions. Growth usually retarded before accumulation to levels dangerous to consumers.
5	**Cobalt (Co)** Toxic threshold of 0.1 mg/ℓ in nutrient solution observed for any plants. Tends to be inactivated by neutral and alkaline soils.
5	**Copper (Cu)** Essential plant nutrient. Toxic to a number of plants at 0.1 to 1.0 mg/ℓ in nutrient solutions.
15	**Fluoride (F)** Inactivated by neutral and alkaline soils provided soil's calcium content is sufficient. On acid sandy soils only 1 mg/ℓ fluoride is allowed (Author's note: The maximum limit recommended for potable water supplies in South Africa is 4 mg/ℓ , hence it is recommended that this limit be the absolute maximum allowed for irrigation water on non-sandy soils in more arid areas, where important aquifers could be at risk.)
20	**Iron (Fe)** Essential plant nutrient. 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 (see also paragraph 3.4.7.2 and 3.4.7.4 under miscellaneous problems).
2	**Lead (Pb)** Not readily absorbed through roots since strongly bound to soil. Recommended levels should protect sensitive crops.

Table 7: (Continued)

Max. Limit (mg/ℓ) *	Effects**
Max. limit above 2.5	**Lithium (Li)** Tolerated by most crops up to 5 mg/ℓ in nutrient solutions; mobile in soil. Toxic to citrus at low concentrations; limit in irrigation water of 0.075 mg/ℓ.
0 - 10.0	**Manganese (Mn)** Essential plant nutrient. Toxic to a number of crops at a few tenths to a few mg/ℓ, but usually only in acid soils. In well-aerated soils manganese concentrations are low in the soil solution.
No max. limit yet.	**Mercury (Hg)** Mostly strongly retained by soil. Natural levels in water are low.
0.05	**Molybdenum (Mo)** Essential plant nutrient. Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentration of available molybdenum. Inactivated at low soil pH values.
2	**Nickel (Ni)** Toxic to a number of plants at 0.5 mg/ℓ to 1.0 mg/ℓ in nutrient solutions; reduced toxicity at neutral or alkaline pH.
0.05	**Selenium (Se)** Toxic to plants at concentrations as low as 0.025 mg/ℓ in nutrient solutions and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element for animals but in very low concentrations.
No max. limit yet.	**Tin (Sn)** Effectively excluded by plants; specific tolerance unknown.
No max. limit yet.	**Titanium (Ti)** Effectively excluded by plants; specific tolerance unknown.
No max. limit yet.	**Tungsten (W)** Effectively excluded by plants; specific tolerance unknown.
0.1	**Uranium (U)** Strongly adsorbed by soil. Recommended limit is conservative.
1	**Vanadium (V)** Toxic to many plants at relatively low concentrations. Interferes with absorption of essential elements.
5	**Zinc (Zn)** Essential plant nutrient. Toxic to many plants at 1 mg/ℓ in nutrient solutions. Reduced toxicity at pH > 6.0 and in fine textured or organic soils.

* Limits applicable for neutral and alkaline fine textured soils for periods up to 20 years at these concentrations.

** As described by Ayers and Wescott (1985)

Table 8: Effluent: Contaminants, effluent sources and associated physical impact (CSIR, 1991)**.**

Contaminants	Source of effluent	Physical impact
Colourants	Pulp and paper, textile, abattoirs, steel, dairy, yeast, tanneries	Aesthetically objectionable, some colour producing pollutants are toxic.
Suspended solids	Pulp and paper, textile, abattoirs, tanning, canning, breweries, steel mills, boiler-house operation, sewage, mining, agriculture, urban	Blockage of sewer lines and equipment, damage to rivers by solids, deposition and oxygen depletion. Interfere with disinfection
Oil and grease	Abattoirs, wool washeries, dairy plants, steel mills, galvanising plants, oil refineries, tanneries, sewage, urban	Blockage of sewer lines and equipment, floating scum on water which prevents oxygen transfer, anaerobic conditions, smell and fly nuisance. Production of objectionable tastes on chlorination
Organic wastes	Pulp and paper, textile, yeast, sugar, abattoirs, tanneries, canning, brewing, starch, sewage, agriculture, urban	Overloading of conventional sewage treatment plants, oxygen depletion in rivers. Objectionable tastes in chlorination, and production of trihalomethanes
Insecticides	Chemical, food, textile, pesticides, agriculture	Toxic to bacterial and aquatic life placing sewage treatment works out of action. Also health risk to man, plants and animals
Trace metals	Pickling, galvanising, plating, mining, urban, power generation, motor vehicle emissions	
Cyanides	Metal finishing, plating, coking, oil refinery, mining	
Chemical wastes	Coking, synthetic dyes, chemicals, plastics, solvents, textile finishing	Taste and odour, toxic to aquatic life, plants, animals and man
Acids (mineral and organic)	Steel pickling, chemical, food, mining, power generation, synthetic fuels, motor vehicles	Corrosion, mobilization of pollutants from sediment, oxygen depletion, acid rain
Alkalies	Metal finishing, plating, pulp mills	Toxic to biota, mobilization of pollutants from sediments
Nitrogen and phosphorus	Fertilizer plants, synthetic detergents, sewage, agriculture	Eutrophication, nitrate may have health implications, ammonia may be toxic to fish
Thermal aspects	Cooling, hypolimnetic discharges	Adverse ecological effects
Detergents	Textiles, metal finishing, sewage	Foaming, possible toxicity
Pathogens and parasites	Hospitals, abattoirs, sewage, agriculture	Spreading of disease
Salts	Mining, agriculture, sewage, many industries	Pose irrigation, industrial and potable water problems
Radioactivity	hospitals, mining, nuclear plants	Genetic damage and health effects

Table 9: Suggested task categories for an effluent to land suitability study.

1 Obtain relevant information on: effluent, crop-type and the site	2 Establish acceptable loading rates, separation distances, volume/ storage values and other data	3 Establish limiting criteria, relevant regulations, and applicable mitigatory measures	4 Derive information for permit-exemption and advisory purposes
(a) For a given effluent and land-use: Identify relevant effluent/ soil-type/land-use characteristics. -------------------------- **(b) For a given site:** Obtain effluent/soils-analysis data. Obtain relevant information on topography and climate. Identify key/ important criteria on geology, geohydrology and hydrology. Identify other important criteria, e.g. adjacent land-uses, land-zoning, site access, etc. -------------------------- **(c)** Identify type of ownership /control over site, eg. private farm, industry, municipal cleansing branch, etc.	**(a) Derive information on:** * (i) effluent contaminant concs. (ii) soil media contents: type and % of soil volume. * effluent application type, monthly volume criteria and nutrient/organic/ toxic-element loading rates. * potentially toxic contaminant conc. levels in soil. ---------------------- **(b)** Given effluent charac-teristics as well as volumetric data: Evaluate suitability of effluent application for soil, crop/ land-use type. ---------------------- **(c)** Identify applicable design and planning parameters, depending on effluent/ land-use type, etc.	**(a)** Determine whether any overriding conditions exist. **(b)** Compare loading-rate data with applicable limits. Highlight limit exceedance/ problem cases, and indicate % reduction required to obtain acceptable annual/ monthly rates, or consider alternative crops/ land-uses, etc. (Allow changes to be made to, and a re-assessment of, volume criteria and loading rates) ------------------------- **(b)** Link overriding and other important conditions to relevant regulations and suitable mitigatory measures, where applicable. Attach relevant recommendations and/or other advice.	**(a)** Indicate whether effluent-type and land-use/ crop type combination is acceptable. Indicate whether effluent/soils contaminant concentrations and site criteria are acceptable. -------------------------------- **(b)** Taking into account the type of ownership /control over site, do the following: Indicate whether the required effluent volume application patterns, etc. are acceptable, and identify suitable protective measures and sampling/ monitoring requirements. Identify other potential problems, suitable measures and further requirements. -------------------------------- **(c)** If all items under **4 (a) and (b)** are acceptable, indicate this and attach relevant planning/design/ management measures. If any items under **4 (a) and (b)** are not acceptable, indicate why not, and what conditions could be considered for a permit exemption status, if required.

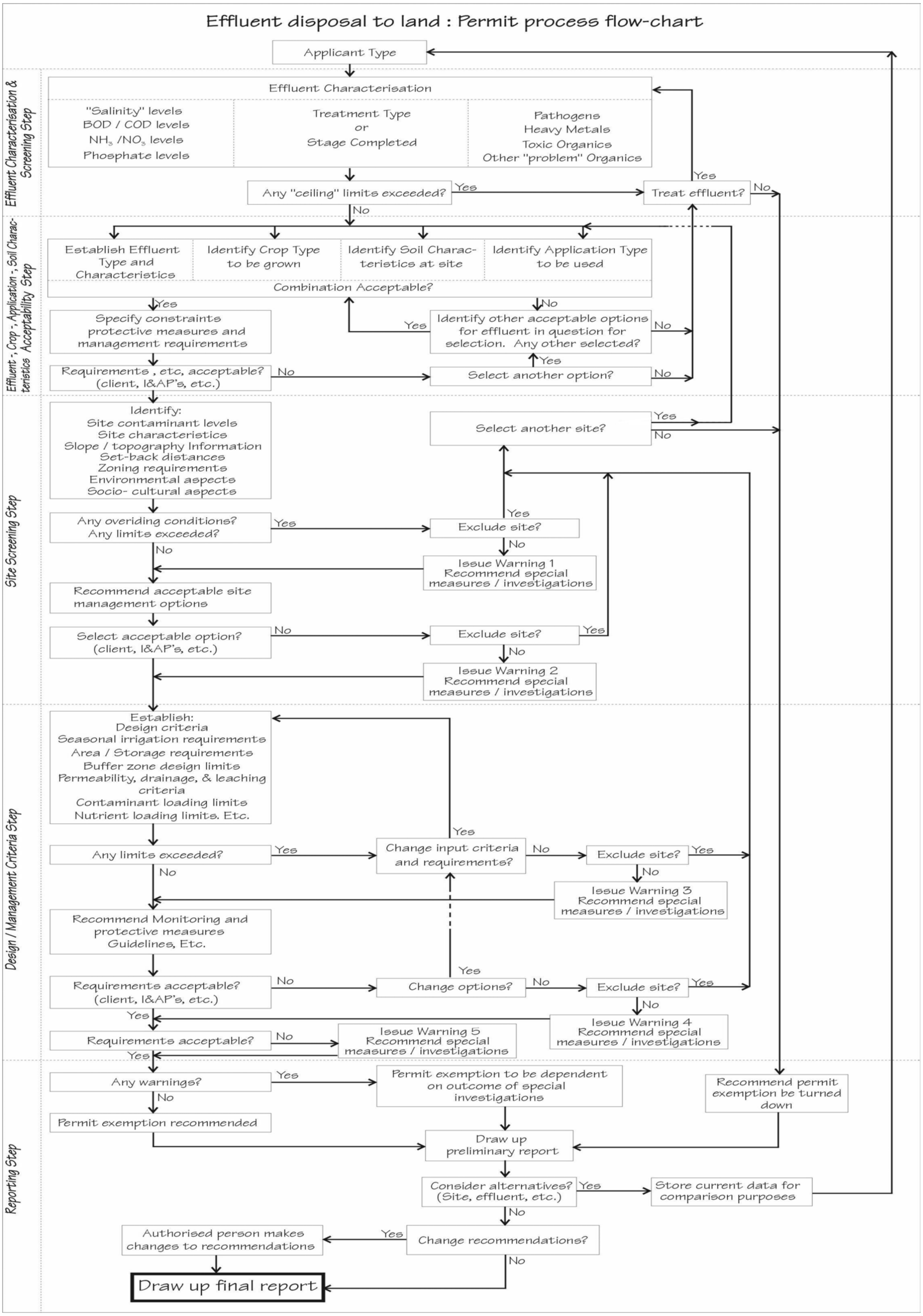

Figure 1. **Effluent to land suitability assessment flow chart - designed to follow an environmental screening approach.**