THE

DEVELOPMENT OF A SYSTEMATIC METHOD FOR EVALUATING SITE SUITABILITY FOR WASTE DISPOSAL BASED ON GEOHYDROLOGICAL CRITERIA

Report prepared for

Water Research Commission

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EXECUTIVE SUMMARY

PROBLEM STATEMENT

Much of South Africa experiences a semi-arid climate. Due to an increasing water demand, sedimentation in dams and a limited number of suitable dam sites, the country will soon face serious water shortages. Even though groundwater only accounts for some 13 % of the total national water supply, approximately 65 % of the area of the country relies on this water source to one degree or another. The predicted inability of surface water resources to meet future water demands and the growing cost of developing these resources suggest that groundwater resources could help meet these requirements, either in conjunction with surface resources or as a sole source. Latest estimates are that over 280 towns and smaller settlements use groundwater to one degree or another.

The disposal of waste has been shown throughout the world to be a major contributor to the degradation of aquifers. Wastes are an unavoidable by-product of all man's activities and the disposal thereof is a growing problem. Approximately 95 % of all solid waste in South Africa is disposed of by landfilling or landbuilding. It is further estimated that 1 400 solid waste disposal sites exist in South Africa. The infiltration of leachate from these sites into groundwater bodies is hence of major concern.

No formalised systems or standard approaches are used to assess the impact that waste disposal sites have, or could have, on South Africa's aquifers. This has led to variable results being obtained and inconsistent conclusions being reached in those geohydrological studies that have been undertaken at waste disposal sites. In response to this, Hall and Hanbury (1990), Jolly and Parsons (1991) and Van Tonder and Muller (1991) all proposed some form of site evaluation based on international literature. However, all were literature-based and the methods have not been tested or validated under South African geological and geohydrological conditions.

RESEARCH OBJECTIVES

The objective of the investigation was to develop and field-validate a South African-based methodology which addressed the geohydrological components of waste site selection and suitability evaluation. The developed method was to be suitable for initial site screening and planning, setting of data requirements and final site suitability determination. Further, a set of required characteristics were identified at the outset. The method was to be:

- *a.* *valid, appropriate and accurate under South African conditions;*
- *b.* *systematic, physically based, objective and the results repeatable;*
- *c.* *suitable for site specific investigations;*
- *d.* *an easy-to-use system based on readily available geohydrological data; and*
- *e.* *the methodology was to be suitable for use by the central government permitting authority, local authorities and private companies entrusted with waste disposal as well as consultants undertaking waste disposal site selection and suitability determination studies*

RESEARCH METHOD

Information concerning site evaluation techniques used elsewhere in the world were collected by means of a

WATERLIT literature search, a South African study tour and a short visit to Europe. The study tours were undertaken in order that in-depth discussions could be held with people active in the field of waste management and groundwater as well as with researchers and developers of other site assessment methods. A total of 29 different site or regional assessment tools were identified and studied. The positive and appropriate features of these methods were then used to develop a conceptual method which took account of South African conditions.

Information from 106 waste site permit applications, submitted to the Department of Water Affairs and Forestry, were examined. Owing to the nature of data presented and the reliability of the data, information from only 71 of these sites could be used in the development of the method. Data pertaining to the type and volume of waste disposed of and the prevailing geological and geohydrological conditions was then collected and used in the verification of the developed method. Information from ten well-studied waste disposal sites, spread throughout South Africa, were used in the validation of the method. Additional fieldwork was required at six of these sites to obtain the required information. The data used in the development, verification and validation of the method is regarded as the best data currently available.

WASTE - AQUIFER SEPARATION PRINCIPLE

*It is widely argued in the literature that most waste can be landfilled without any unacceptable detriment to the public or the environment if the sites are carefully selected. Further, if expensive and technically difficult groundwater contamination clean-up is to be avoided, waste facilities and aquifers must be kept apart. This separation concept is central to the method developed and led to the name **Waste - Aquifer Separation Principle**, abbreviated as **WASP**.*

Three factors were identified as being important in the assessment of site suitability for waste disposal (Figure 1), namely:

- *the Threat Factor*
- *the Barrier Factor*
- *the Resource Factor.*

Many of the methods studied subscribed to a similar concept. One of the major differences between WASP and vulnerability mapping techniques is that vulnerability mapping does not consider the actual threat posed by the waste pile. The fact that the three elements were so distinct and easily differentiated between, in terms of both role played and actual physical boundaries, made this approach attractive.

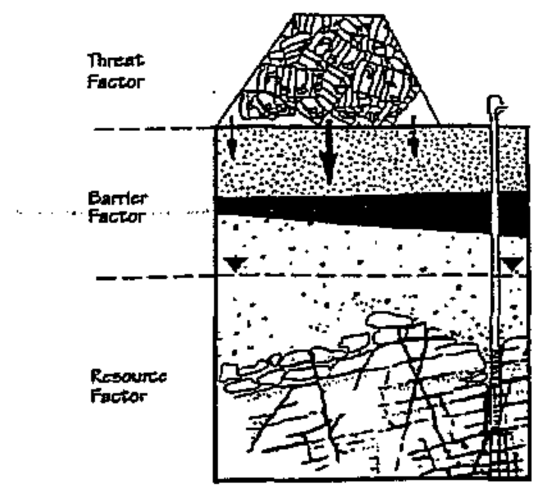

Figure 1: The three factors which impact on site suitability for waste disposal

Threat Factor

All waste disposal sites produce leachate and, as such, pose a threat to groundwater resources. The threat posed is essentially some product of the volume of leachate produced and the quality of that leachate. Both components are extremely difficult to quantify or predict with any certainty. After due consideration was given to international trends and current South African practice, it was decided that a Threat Factor score could be obtained using the designed final area of the site and the type of waste being disposed of.

Barrier Factor

The barrier between a waste pile and an aquifer is represented by the unsaturated zone. It is within this zone that much attenuation of leachate occurs. Important processes in leachate attenuation include chemical precipitation, adsorption, dilution, dispersion and biodegradation. Attenuation is a set of complex and often inter-related processes governed by a number of factors. The modelling of attenuation processes is hence extremely difficult. It was therefore decided that the time that leachate would take to travel from the base of the waste pile to the top of the aquifer would be used to quantify the ability of the barrier zone to separate the waste from an aquifer. Travel time is calculated using Darcy's Law. The data required for the calculation are depth to water and the hydraulic conductivity and porosity of the vadose zone. The Barrier Factor score is obtained by comparing the calculated travel time to a rating curve.

Resource Factor

*The quantification of the Resource Factor proved to be most challenging. In attempting to establish the significance of a groundwater body, and then employing a single number to reflect the value of the resource, one is essentially trying to present the science of geohydrology in a short sentence. It was decided at the outset that the **strategic value** of a groundwater body to its user, or potential user, should be considered. This meant that a single user, such as a farmer, was given the same weighting as a large multiple user, for example a town. This required that measurable and definite parameter values be excluded from the assessment process. A questionnaire approach was shown to be the most appropriate means of assessment. Two sets of questions were compiled, the first set dealing with current usage and the second with potential usage. Points are awarded for each answer, thus enabling the quantification of the Resource Factor.*

WASP Index

Once scores for all three Factors have been determined, the WASP Index is computed using a nomographic solution. The obtained Index can be correlated directly against a generalised interpretation, whereby sites are defined as being either highly suitable, suitable, marginal, unsuitable or highly unsuitable. The interpretation was developed and refined using information obtained from the 71 permit applications and the associated reports.

Data Reliability

In order that WASP could have a wide application, a data reliability rating was developed. Each input data considered by WASP is rated in terms of its detail and reliability. A simple rating scale of 1 to 3 is used. The three data reliability levels used correspond directly to the types of investigations which may be required by current Integrated Environmental Management principles and procedures. Once all data have been rated, an average is obtained and recorded in brackets after the obtained WASP Index. The data reliability rating allows that the value and reliability of the WASP Index be readily apparent. This aspect will be particularly valuable to DWAF when considering waste site permit applications.

Flexibility

It was found during the development of WASP that not all geohydrological situations could be accommodated in the procedure. At times, one component or Factor was so dominant that it over-rode the determined WASP Index. Extremely poor groundwater quality, a very slow travel time through the barrier and an extremely low groundwater potential were three commonly encountered conditions which resulted in over-ride situations. The inclusion and identification of over-ride factors was thus accommodated in WASP to account for such circumstances and hence provide flexibility in the procedure. The employment of an over-ride during site *evaluation, however, can only be based on detailed and reliable data and be motivated by a suitably qualified and experience geohydrologist.*

DISCUSSION

The validity of WASP was assessed by comparing the WASP Indices obtained for the 10 waste disposal sites studied in detail with observed contamination patterns. All of the obtained indices were found to be accurate assessments of the prevailing conditions. Further validation is nonetheless recommended once more data becomes available.

The integration of WASP, at all levels, into broader waste site suitability assessment procedures and approaches will provide much assistance and impetus to the prevention of contamination of South Africa's aquifers by waste disposal activities. WASP can play a valuable role in initial site screening, identification of additional data requirements and the final assessment of the a suitability for waste disposal. The incorporation of WASP into the current waste site permit application procedure is also seen as being particularly important.

Even though every effort has been made to develop an accurate and reliable tool, WASP does have some limitations. These result largely from the assumptions and simplifications used in WASP. Users of the method must thus be aware of these inherent limitations. WASP does not replace the need for appropriate data and information, nor the need for suitable geohydrological training and experience, in the assessment of site suitability for waste disposal. The procedure is merely a tool to help in the evaluation of proposed and existing sites and promotes sound decision-making. The reliability of the assessment remains a function of the data used and the expertise of the assessor.

A field manual has been prepared so that the procedure can be easily applied under field conditions. Further, software has been written which allows for the easy input of the required data and the automatic calculation of the WASP Index and the interpretation thereof.

CONCLUSIONS

Based on all the reliable waste disposal site data currently available in South Africa and the work performed during the research programme, WASP was found to be capable of providing an accurate and quantified assessment of a site's suitability for waste disposal, based on geohydrological criteria. WASP now needs to be applied to a wide range of waste and geohydrological conditions. Once applied, the performance of the procedure can then be re-assessed.

The objectives of the research project have been achieved by the development, verification and validation of the Waste-Aquifer Separation Principle, abbreviated as WASP. The method was based on 29 methods used throughout the world, but was developed to suit South African conditions. All reliable waste disposal site data currently available were used in the verification of the method while the validation of WASP was based on information from ten well-studied facilities spread throughout the country. A data reliability rating is coupled to the WASP Index and this allows the value and reliability of the obtained Index to be readily apparent. A degree of flexibility is allowed for in the procedure in order to accommodate special or unique considerations and circumstances. WASP does not, however, replace the need for appropriate data nor the need for the assessor to be suitably qualified and experienced in geohydrology.

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Mr AG Reynders	Water Research Commission (Chairman)
Mr JM Ball	Institute of Waste Management
Mr L Bredenhann	Department of Water Affairs and Forestry
Mr HM Du Plessis	Water Research Commission
Dr B Hambleton-Jones	Atomic Energy Corporation of South Africa
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Mr M Simonic	Department of Water Affairs and Forestry
Mr F Viviers	Department of Health and Population Development
Mr J Weaver	CSIR
Mr D Huyser	Water Research Commission (Secretary)

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1. INTRODUCTION

1.1. Problem Statement

It is well recognized that much of South Africa has a semi-arid climate. Due to a rapidly expanding population, a shortage of additional dam sites and the loss of surface water storage capacity due to erosion and sedimentation in dams, it is predicted that by the year 2010 the country will face serious water shortages (DWAF, 1986). Even though groundwater only accounts for 13 % of the total national water supply, approximately 65 % of the area of South Africa relies on this water source to one degree or another (Braune, 1990). The predicted inability of surface resources to meet future water demands and the growing cost of developing these resources suggest that groundwater resources could help meet these demands, either in conjunction with surface resources or as a sole source. Already this trend is being noticed. Vegter (1984) stated that 105 towns rely on groundwater as a sole source, while a further 15 towns use groundwater in conjunction with surface supplies. The latest estimates are that more than 289 towns and smaller settlements use groundwater to varying degrees (DWAF, 1992).

The disposal of waste has been shown throughout the world to be a major contributor to the degradation of aquifers (Lisk, 1991; Stone, 1991; Skinner,1990; Farquhar, 1988). Wastes are an unavoidable byproduct of all man's activities and the disposal thereof is a growing problem. Much of the waste is discarded on land in a similar fashion at either landfill or landburial facilities. Municipal domestic refuse, sewage sludge, industrial effluent and mining wastes are examples. A highly contaminated liquid containing chemical, biological and bacteriological constituents is formed when water passes through decomposing refuse and waste piles (Hojem, 1989). The infiltration of this leachate into aquifers results in a degradation of groundwater quality and the rendering of a resource unfit for further use.

It has been shown that the clean-up of a contaminated aquifer is both technically difficult and expensive (Olsen and Kavanaugh, 1993; Stone, 1991; Travis and Doty, 1990; Schwartz, 1988; Jsvoma, 1985). The USA situation is cited as an example of the economics of rectifying past mistakes. The SUPERFUND was set up in order to clean up groundwater contamination emanating from disposal facilities. A total of $ 8 billion dollars had been budgeted for until 1992 for financing the programme (Skinner, 1990). Odendaal (1991 quoting Holland, 1990) notes that the cost of cleaning up the 1 800 waste sites on the National Priorities List (NPL) could cost $ 14,6 billion. Stone (1993) estimated that about $ 1 000 000 is spent *each hour* in the USA on aquifer remediation activities. Further, of the hazardous waste sites designated on the NPL list, only 27 of the 1224 posing the greatest risk to human health have been cleaned up and removed from the list during the past 10 years. Travis and Doty (1990) stated that in meeting the challenge of waste disposal, groundwater contamination and aquifer remediation, it needs to be explicitly acknowledged by all parties that aquifer restoration is currently technically impossible.

With the present economical and political situation and the increasing demand on the dwindling water resources of South Africa, this country can ill afford to spend large sums of money rehabilitating aquifers. Further, a pro-active approach as opposed to the current reactive approach is desirable. The protection of groundwater resources, especially sole-source aquifers, is thus an important issue in the national water supply strategy.

In addition to reducing waste volumes, two approaches to limiting and / or preventing groundwater pollution from waste disposal sites can be used (Hatheway, 1990):

a. correctly siting a waste disposal facility in suitable geological and geohydrological environments.
b. engineering a site with liners or clay horizons thereby retarding leachate infiltration into the subsurface environment.

Stone (1991) argues that the only sure formula for the peaceful coexistence of landfills and aquifers is by their separation. He states that "there is ample evidence that liners will eventually fail" (p. 10) and that "the concept of a forever safe sealed landfill does not seem to be a practical long term solution to safeguard the integrity of water resources" (p. 11). He, together with Holmes (1989) and Mitchell (1986), state that most controlled waste can be landfilled without any unacceptable detriment to the public or the environment *if the sites are carefully selected.* In terms of protecting groundwater resources, the hydrogeological setting is paramount among criteria for site acceptability.

The selection and suitability determination of disposal sites requires a multi-disciplinary approach owing to the many aspects that require consideration. The geohydrological factors that need to be appraised during this process are complex, inter-related and the relative importance of these factors may differ from place to place. A number of methods and systems are presented in the literature for evaluating a site's suitability for waste disposal (Holmes, 1989; Kerkhof et al., 1987; Roa et al., 1985; Kufs et al., 1980; Le Grand, 1980, 1964; Phillips et al., 1977 and others). Possibly the best known and documented is the DRASTIC method which is a standardized system for evaluating aquifer vulnerability on a regional scale (Aller et al., 1985). DRASTIC was developed for the United States Environmental Protection Agency (EPA).

In South Africa no formal or standardized site evaluation methods are used. Most investigators use their own system, based on their experience and level of expertise. This has resulted in a non-uniform and subjective approach which is open to conflicting interpretation. In response to the lack of a South African formal methodology for evaluating the suitability of waste disposal sites, Jolly and Parsons (1991), Van Tonder and Muller (1991) and Hall and Hanbury (1990) have all proposed some form of evaluation method based on international literature. However, all are desk-based and the methods have not been validated in the field under South African geological and geohydrological conditions. CSIR and the Department of Water Affairs and Forestry (DWAF) thus approached the Water Research Commission (WRC) to fund a joint research project aimed at developing a methodology for evaluating waste disposal sites based on geohydrological considerations.

1.2. Research Objective

The *objective* of the investigation was:

> to develop and field-validate a South African-based methodology which addresses the geohydrological components of waste site selection and suitability evaluation.

The following *applications* of the evaluation system were defined at the outset of the investigation:

a. initial site screening and planning
b. setting of data requirements to be obtained from fieldwork
c. final site suitability determination

The method is to be nationally applied such that standardization of site evaluation is attained. Further, the system is to have the following *characteristics*:

a. it is to be valid, appropriate and accurate under South African conditions
b. the method is to be systematic, physically based, objective and the results repeatable
c. it is to be suitable for site specific investigations
d. it is to be an easy-to-use system based on readily available geohydrological data
e. the methodology is to be suitable for use by the central government permitting authority, local authorities and private companies entrusted with waste disposal as well as consultants undertaking waste disposal site selection and suitability determination studies

It must be stressed that the final product of the study cannot be expected to replace expert geohydrological input nor the need for appropriate fieldwork when selecting and evaluating waste disposal sites.

It was decided at the outset by the Steering Committee that engineering aspects were not to be considered in the method. Cognaisance was, however, taken of engineering aspects and requirements.

1.3. Report Structure

The result of this research initiative is presented in three forms, namely this scientific research report, a manual and a disc containing the software version of the method.

Following the introductory chapter of this report, a brief review of the role of groundwater resources in South Africa, as well as an appraisal of current waste disposal practices, are presented in Chapter 2. In Chapter 3, the methodology followed in the research programme is described. Site evaluation and selection methods identified during the literature study are discussed in Chapter 4, while geohydrological factors which impact on the suitability of the site for waste disposal activities are addressed in Chapter 5.

The Waste - Aquifer Separation Principle (WASP) developed during the research project is presented in Chapter 6, while the quantification and verification of WASP is described in Chapter 7. The application and limitations of the methodology are examined in Chapter 8. Conclusions and recommendations constitute the last Chapter of the report.

The WASP manual is presented as Appendix E of this report and also as a separate field manual so that it can be conveniently transported and used under field conditions. The WASP software requirements, installation procedures and operation instructions are presented as an appendix in the manual.

2. GROUNDWATER RESOURCES AND WASTE DISPOSAL IN SOUTH AFRICA

2.1. Groundwater

2.1.1. Water supply in South Africa

South Africa is not blessed with ample water resources as approximately two thirds of the country experiences a semi-arid climate. The national average annual rainfall is only 497 mm/a and 21 % of South Africa receives less than 200 mm/a (DWAF, 1986). Rainfall is erratic and the country is periodically afflicted by severe and prolonged droughts which are often terminated by severe floods. Further, evaporation rates are high and only 20 % of the area of South Africa can be regarded as water surplus areas ie. where precipitation exceeds evaporation (Ball, 1984). In addition to natural limitations, high soil erosion rates, a limited number of suitable dam sites, distance to point-of-need and deteriorating water quality also emplace restrictions on the development of surface water resources.

The supply of water in South Africa is no easy task. It is becoming more and more difficult as water demand increases as a result of an increasing population; increasing mining, industrial and agricultural water demand; and improved living conditions. It has been estimated that domestic water demand for most major metropolitan areas will continue to grow at a rate of 5 % p.a. (DWAF, 1986). In these areas, water demand will exceed supply by the year 2010. For example, in the Cape Town and the Durban - Pinetown - Pietermaritzburg areas, this will occur in 2008 and 1999 respectively. Conventional resources which are distant from point-of-need are having to be developed at great expense to avoid the looming crisis. Examples include the Lesotho Highlands Scheme for the Pretoria - Witwatersrand - Vereniging (PWV) area and the emergency Sundays River Scheme for Port Elizabeth.

It has been recognised that conventional sources are finite and that alternative water sources have to be investigated. Water reuse, recycling, desalination, rainfall augmentation, water harvesting, icebergs and importation from neighbouring states are receiving or have all received attention. Means of reducing water demand by optimizing usage are also being seriously considered. It is, however, clear that the cost of water will steadily rise in the future as the natural limits of water resources are neared.

2.1.2. Groundwater usage

The role of groundwater is often underplayed in terms of it's importance to the national water supply strategy. Groundwater accounts for only 13 % by volume of present total water demand but approximately 65 % of the area of South Africa relies on this resource for water. This is particularly true for the drier western portion of the country and the sparsely populated areas away from the major metropolitan areas. The use of groundwater appears to have increased substantially over the last decade. In 1984, Vegter reported that 105 towns used groundwater as a sole water source and 15 towns use groundwater in conjunction with surface supplies. Five years later, estimates by Kok and Simonis (1989) showed that 280 towns and smaller settlements relied on groundwater totally or partially. Urban groundwater users include Pretoria, Verwoerdburg, Uitenhage, De Aar, Graaff-Reinet, Atlantis and Bushmans River Mouth.

If the use of groundwater per sector is considered (Table 1), by far the greatest user of groundwater is the irrigation sector (DWAF, 1992). Further, if the agricultural sector is treated as a whole, then approximately 88 % of all groundwater used in South Africa is by this sector. The economic value of groundwater to the agricultural sector, be it for irrigation, stock watering or household use, is thus almost immeasurable.

Table 1: Users of groundwater in South Africa.

Water Use Sector	Use (% of Total groundwater use)
Urban (incl. industrial and mining use from public sources)	4
Rural domestic	7
Stock watering	6
Irrigation	78
Mining and quarries	5

(DWAF, 1992)

Because of dwindling surface supplies and the advantages of using groundwater for water supply, this resource will have to play an increasingly important role in the future, particularly in the urban and peri-urban areas. Some of these advantages are:

a. groundwater is between 3 and 5 times cheaper to develop than surface resources (Wright and Parsons, 1994; Johnstone and Snell, 1993; Braune, 1990).
b. groundwater schemes can be progressively developed over a period of time which delays capital expenditure.
c. groundwater is well suited to augmenting surface water supply schemes during droughts or periods of peak water demand.
d. groundwater is ideally suited to meeting the water demands of rural and developing communities.

The perception that groundwater is not an important viable resource in South Africa could be the result of the following:

a. groundwater is an intangible resource which cannot be seen and hence is poorly understood by people outside the geohydrological field.
b. in general terms, groundwater cannot yield the vast quantities of water needed to meet the total needs of large South African metropolitan areas.

c. groundwater is often regarded as an unreliable resource, but supply scheme failure is often a function of poor or non-existent resource management, as opposed to the limitations of the resource itself.
d. lack of geohydrological expertise at a local level.

These perceptions are, however, slowly changing as a result of educational efforts by, amongst others, WRC, DWAF, the Groundwater Division of the Geological Society of South Africa, the Borehole Water Association and the success of groundwater supply schemes at places like Port Alfred. Here, good quality groundwater abstracted from the beaches of Port Alfred kept the town in water when the Mansfield Dam was dry and while the new off-channel Sarel Haywood Dam was being built. This emergency scheme, which was initially designed to see the town through the 1981 peak summer holiday season, is still being used 13 years later to supplement and improve the quality of the surface supplies (Weston, pers.comm., 1992). It is surely just a matter of time before all groundwater resources are forced to be developed to their optimum potential. The groundwater resources may be used to supply small to medium sized towns as either a sole source or in conjunction with other resources as well as supplement water supplies to larger towns and cities in a small but significant manner, as is the case in Pretoria and Madrid (Braune, 1990).

The above discussion has highlighted the water supply shortage problems and challenges facing South Africa in the next twenty years. The viability and importance of the role of groundwater in meeting present and future demand, even if only in a small capacity, has also been highlighted. Based on the potential role of groundwater in meeting these challenges, the need to protect groundwater resources becomes vital.

2.1.3. Groundwater contamination by waste disposal activities.

Pollution caused by land-based waste disposal activities on all components of the hydrological cycle has been well documented and is no longer a disputed fact (Stone, 1991; Lisk, 1991; Kross, 1991; Farquhar, 1988 and others). World literature abounds with case studies of serious groundwater contamination occurrences, preventative actions that can be taken, groundwater remedial activities, current research in the field and other related topics (DWAF, 1994a, 1993; M[c]Combie and M[c]Kinley, 1993; Nagelhout et al., 1992; US EPA Ground Water Task Group, 1991; Palmer and Young, 1991; Rathje, 1991; Sangodoyin, 1991; Barker et al., 1988; Heath and Lehr, 1987; Friesel et al., 1985; Tredoux, 1984).

The Love Canal saga in the USA gained a tremendous amount of exposure in both the press and scientific literature, probably because it was one of the first cases which clearly showed the impact of waste disposal on groundwater and the dire consequences thereof. The site started out as a piece of canal that was never completed and ended up receiving approximately 22 000 tons of chemical wastes between 1942 and 1953 (Schwartz, 1988). The earliest problems were first recorded in 1976 and included:

a. subsidence of the landfill surface and exposure of drums.
b. ponding of contaminated surface water in backyards adjacent to the landfill.
c. the presence of unpleasant odours which caused "discomfort and illness" to the residents.
d. migration of chemicals into basements adjacent to the landfill

e. chemical migration into and through the local sewer system.

"Subsequent health studies that indicated a predisposition towards spontaneous abortion and low birth-weights in infants prompted an emergency to be declared at the site. This measure resulted in the evacuation of 236 families from the site" (Schwartz, 1988). A second state of emergency was declared in 1980 when additional testing of residents revealed chromosomal abnormalities.

Love Canal focused the world's attention on the problem of groundwater contamination and revolutionised the geohydrological industry with the emergence of the sub-science of contaminant hydrogeology (Schwartz, 1988). A tremendous effort was initiated in:

a. developing and implementing legislation
b. carrying out detailed theoretical and practical research programmes
c. developing and refining new and old technologies

These activities undoubtedly led to a development and improvement of the science as a whole. Detailed handbooks and manuals can now be easily obtained on almost any geohydrological subject. Modelling of groundwater and plumes also made great strides. The "revolution" emphasised the difficulty in translating theoretical and laboratory-scale studies into practice and as a result, work is now more focused on actual field conditions. Pro-active measures, such as wellhead protection zones, are being implemented as a means of protecting groundwater resources. The exact impact and effect of new technologies and approaches are being tested and evaluated with time, leading to a dynamic science which is continually improving.

The implementation of legislation in the USA had a number of positive impacts on solving the waste problem, with the reduction of the number of sites probably being the most important. Stone (1991) reported that 14 000 or 70 % of active waste sites were closed in the USA between 1978 and 1988. Today there are only 6 000 active sites left of which 3 000 will be closed by 1995. Effective legislation in West Germany yielded similar results. Even though the closed sites still require attention, at least the problem will be geographically concentrated in the future.

The economic benefits of pollution prevention have also been brought to the fore. A recent press report presented the example of a pending court case against a company in the USA. If found guilty, the Chief Executive Officer, who is held liable for his company's actions, faces a jail term of 25 years and the company a fine of $ 45 million. The 3M company, on the other hand, adopted a "Pollution Prevention Pays" principle with the aim of turning environmental concern into profit. Hayward (1990) estimated that by doing so the company saved about $ 500 million world-wide over a 10 year period.

The change in approach to waste disposal and the science has also had many disappointments. Stone (1991, p. 2) remarked that "garbage disposal and hazardous waste problem has become big business." Billions of dollars continue to be spent on litigation. Besides boosting the legal profession, the geohydrological community also blossomed. Some research went to extremes - a tracer experiment at Cape Cod, Massachusetts used 656 multi-level sampling points spread over an area of no more than three rugby fields ie. 300 m by 150 m (LeBlanc et al., 1991). Odendaal (1991) notes that for every dollar spent on SUPERFUND projects, 44 cents goes to administration, litigation and related expenses, 16 cents for site studies and only 40 cents for actual cleanup work.

The greatest disappointment of the American waste disposal initiatives must, however, surely be the inability to restore contaminated aquifers and the amount of money spent on this activity (Olsen and Kavanaugh, 1993; Lee and Jones, 1991; Jackson et al., 1989). Love Canal prompted action under the SUPERFUND Law to begin the clean-up of contaminated sites across the United States. The goal of SUPERFUND was to achieve protection of human health and the environment by preventing contamination and restoring groundwater to a quality suitable for beneficial use. The NPL was drawn up and lists those sites which pose the greatest risk to human health and are in need of urgent attention. Estimates of the number of sites that will be placed on the NPL range between 2 000 and 10 000 (Schwartz, 1988). However, only 27 of the 1 224 NPL sites have been remediated to sufficient standard and thus removed from the NPL over the last 10 years. This amounts to a success rate of a mere 2,7 waste sites per year for the whole of the USA at a cost of millions of dollars. In their evaluation of the SUPERFUND programme, Travis and Doty (1990) note that 68 % of SUPERFUND sites are being remediated using the pump and treat method. Even though contaminant concentrations have dropped, they failed to find one case where successful remediation was achieved using this method even after some sites had been pumped continuously for 10 years. They also state that as soon as pumping ceases, contaminant concentrations rise. Travis and Doty (1990) concluded that technologies are not presently available to restore contaminated aquifers.

In the learning process, many misconceptions emerged. Stone (1991), in his evaluation of the waste problem in the USA, argued that waste disposal sites will always require some form of management. He cites the case of 2 000 year old Roman landfills which are still today producing leachate. Based on US EPA documentation, Stone argues that even the best liners and leachate collection systems will fail at some point and hence do not safe-guard groundwater systems. He stated that landfill siting criteria and engineering design will only determine whether the impacts are immediate or delayed. A period of about thirty years has been generally assumed to be adequate for landfills to stabilize in terms of chemical activity. This, Stone claims, is applicable to methane gas generation, but not to leachate generation. Based on these considerations he states that the only way in which landfills and aquifers can peacefully co-exist is to keep them separated. He further warns, together with Parsons (1994) and Lee and Jones (1992), that a false sense of security should not be allowed to develop when leachate is not detected in monitoring boreholes or collection systems, as it could take many tens of years before the fill reaches its leachate generating capacity. Only then will leachate migrate from the waste pile to the monitoring boreholes.

Many other aspects of waste disposal and its impact on groundwater resources could be discussed here. The American situation has, however, brought to the fore a number of important issues:

a. groundwater contamination by waste disposal is like a hidden time-bomb ready to explode years after it was first activated - the impacts, when eventually felt, are horrific and irreparable.
b. the waste problem is a life-long one - in geological terms.
c. the science and technologies used to address the problem are rapidly developing but are still imperfect and have, as yet, not stood the test of time.
d. what was done yesterday is often proved wrong today.
e. coping with the problem is an expensive process.
f. groundwater restoration is not technically possible - a pro-active as opposed to a reactive approach is required.

Based on these and other considerations, it is clear that a preventative approach is desirable. The correct siting of a waste disposal facility is the first step in protecting the integrity of groundwater resources (Stone, 1991; US EPA Ground Water Task Group, 1991; Macachlan et el., 1990; Al-Bakri et al., 1988; Jsvoma, 1985; Goldstein, 1984 and others). It must, however, be recognised that a number of factors other than hydrological considerations impact on the suitability of a site for waste disposal. These include:

a. distance from waste generators,
b. existing infrastructure,
c. environmental impacts,
d. aesthetic impacts, and
e. availability of cover material.

As the method developed during this research effort only considers geohydrological criteria, it is merely a part of a greater integrative and holistic approach to the assessment of site suitability for waste disposal.

2.2. Waste Disposal in South Africa

2.2.1. Legislation

The CSIR investigation (CSIR, 1991) identified 37 national statutes, 16 provincial ordinances and numerous by-laws dealing with waste. To quote from Myburgh (1991, p. 23):

> *"The multiple overlaps in jurisdiction, coupled with the absence of a hierarchy of authority, results in the fact that no Department and no individual is in charge, which in turn has the effect that no one is accountable for the management of the environment as a whole. To coin a phrase, the net result is bureaucratic paralysis".*

At present, DWAF is entrusted to ensure that waste disposal is carried out in a responsible manner. The most important Acts through which acceptable, responsible disposal is controlled are:

a. the Environment Conservation Act, Act 73 of 1989 and the Environment Conservation Amendment Act, Act 79 of 1992,
b. the Water Act, Act 54 of 1956,
c. the Health Act, Act 63 of 1977.

2.2.1.1. The Environment Conservation Act

The Environment Conservation Act, including it's amendments, is the only Act dealing specifically with the disposal of waste. Sections 20, 21, 22, 24, 24A, 26, 29 and 30 of the Environment Conservation Act relate specifically to management. These Sections prohibit the disposal of waste other than at a waste site. Further, the site may not be established or operated without a permit issued by the Minister of Water Affairs and Forestry - in the application for this permit the Minister may prescribe what information must be submitted by the applicant. The Minister may at any time promulgate directions with regards to the control, management and closure of waste sites. The Act further empowers the Minister to make regulations regarding waste management. Section 29 of the Act deals with offenses and penalties. As far as waste disposal is concerned, the section makes it an offence to operate a waste disposal site without a permit, or in contravention of the provisions of the permit, or the regulations framed by the Minister in connection with the operation of waste disposal sites. The maximum penalty for such an offence is a fine of R 100 000 or imprisonment for a period not exceeding ten years, or both such fine and imprisonment. Bearing in mind the serious consequences which may result from the improper disposal of waste, these penalties certainly appear to be more in keeping with the gravity of the offence than those contained in the other Acts referred to below (Myburgh, 1991).

2.2.1.2. The Water Act

It is significant that control of waste management is, in terms of the Environment Conservation Act referred to above, not vested in the Minister of Environmental Affairs, but rather in the Minister of Water Affairs and Forestry. Considering that the most serious consequence of failure of a poorly managed waste disposal site is the pollution of water supplies, it is logical that this control lies with the DWAF. The Water Act contains important provisions with regards to the prevention of pollution of water, this being a very real threat in the context of waste disposal. The provisions regarding the prevention of water pollution are contained in Sections 21, 22, 23, 24 and 26 of the Act.

The Water Act also provides for offenses and penalties. These penalties are lower than those under the Environment Conservation Act, a fine of R 10 000 and / or imprisonment not exceeding 12 months on a first conviction and a fine not exceeding R 20 000 and / or imprisonment not exceeding 12 months on a subsequent conviction.

2.2.1.3. The Health Act

Since waste disposal can under certain circumstances constitute a health hazard, certain provisions of the Health Act including the amendments of 1992, have an important bearing on waste disposal. Section 20 of the Health Act imposes a positive obligation on local health authorities to ensure that hygienic conditions are maintained and to take steps to rectify any conditions, including waste disposal, which may constitute a threat to public health. Fines are limited to a maximum of R 500 and / or six months imprisonment on the first offence.

2.2.2. Current Practice

Industrialization and the development of hazardous wastes has occurred later in South African than in most First World countries. South Africa, however, with a population of approximately 40 million people, produces some 300 million tons of solid waste annually. The various contributors to this total are shown in Table 2. Six million tons of this waste can be classified as hazardous (CSIR, 1991).

Ninety five percent of all solid wastes generated are disposed of by landbuilding or landfilling. Considering that mining tailings and fuel ash are excluded from the legal definition of waste, the remaining 5 %, which amounts to an approximate volume of 35 million tons per annum, must comply with the Environment Conservation Act.

CSIR (1991) identified approximately 1400 solid waste disposal sites in South Africa. By April 1994, one hundred and ten of these sites had been granted their permits in terms of Section 20 of the Environment Conservation Act (Bredenhann, pers. comm., 1994). The remainder are in the process of applying for permits. Parsons (1992) identified a lack of staff as one of the primary reasons for the slow progress in issuing permits. Financial constraints also limit the undertaking of the investigations required.

In the investigation and assessment of waste disposal sites in South Africa, no standard site selection criteria are used. In general one or two factors are considered, these being geology and groundwater use. Some workers such as Hall and Hanbury (1990), Jolly and Parsons (1991) and Van Tonder and Muller (1991) either applied certain methods or developed their own procedures.

Table 2: Solid waste stream, as measured in 1990

Type of Waste	Volume (tons / year)
mining tailings	238 500 000
pulverised fuel ash	22 200 000
urban waste	15 000 000
chemical waste	12 200 000
metallurgical slags	5 400 000
other waste	4 800 000

(CSIR, 1991)

2.2.3. Current Research

At present, research into groundwater contamination and waste disposal is receiving attention from WRC, DWAF and the Department of Environment Affairs (DEA). A list of recent and current research closely aligned to this project is presented in Table 3.

2.2.4. State Initiatives

DWAF currently administers the permitting of waste sites in compliance with Section 20 of the Environment Conservation Act. The permit application procedure is outlined in a DWAF guide entitled "Waste Management Legislation : Procedures and Guidelines" (Bredenhann et al., 1991). The permit issuing procedure is as follows:

a. discussions between the Department and the site owner culminating in the completion of the application form.
b. an iterative process between the applicant and the Government Departments involved, during which certain information will be requested. The number and extent of these reports will depend on the amount and type of waste being disposed of and the characteristics of the

Table 3 : Waste disposal related research projects

RESEARCHERS	STUDY TITLE
CSIR	The situation of waste management and pollution control in South Africa (DEA Project)
Meyer, Tredoux, and Weaver (CSIR)	Evaluation and development of geophysical techniques for characterizing the degree of groundwater pollution at waste sites (WRC Project).
Verhagen and Levin (Wits. Univ. and AEC)	The development of geohydrological and isotope hydrological methodologies for the identification of areas potentially suitable for waste disposal (WRC Project).
DEA	Hazardous waste in South Africa (DEA Project)
Weaver (CSIR)	Groundwater sampling manual (WRC Project)
Reynders (WRC)	An investigation of aquifer vulnerability and pollution risk in formulating a groundwater quality protection strategy for South Africa (Ph.D. study at IGS, University of OFS).
Murphy (CSIR)	Development of an expert system method for the selection of suitable landfill sites and guidelines for sanitary landfill in municipal areas (WRC Project).
Ball et al. (Rod Ball and Associates)	Minimum requirements for waste disposal sites (DWAF Project).
Fourie (Ockie Fourie Toxicologists cc)	Minimum requirements for management and handling of hazardous wastes (DWAF Project).
Hodgson (IGS)	Minimum requirements for the monitoring of waste management facilities (DWAF Project).
Parsons (CSIR)	A Review of approaches and methodologies for determining leachate generation at waste disposal sites and groundwater recharge (WRC Project)

environment in which the site is located. Some or all of the following reports could be required; geohydrological report, environmental impact report, design and engineering plan, operation plan, water quality monitoring plan and a closure and rehabilitation plan. Usually a Phase 1 or Feasibility report is requested as a first step. The objectives of the Feasibility Report are to confirm that the site has no fatal flaws, to identify any potentially significant impacts and to satisfy the various Departments involved that the site is suitable for further detailed investigation. Should the site be found to be feasible, then more detailed reports are submitted to prove the site is satisfactory for development.

c. once the Government Departments are satisfied with the information presented a Motivation Report is compiled and a permit will be issued.
d. the permit could either have conditions controlling the future operation of the site, or may have conditions requiring the closure of the site.
e. the control and monitoring of the site take place once the site has received it's permit.
f. six months before closure, documents must be submitted by the site owner on final closure and rehabilitation.
g. the site is closed to the satisfaction of the Department.
h. post closure monitoring of the site takes place.

In order to ensure that waste is disposed of in an environmentally acceptable manner, the DWAF is presently involved in studies to establish Minimum Requirements for waste disposal facilities. Minimum requirements may be defined as norms used to distinguish between acceptable and non-acceptable waste management practices (Bredenhann et al., 1991). A manual, available for use by Government Departments, consultants and permit holders is envisaged. The manual will cover the logical sequence of events associated with the development of a waste site, namely - siting, site investigation, design, construction, management and closure.

To be practically implementable, the Minimum Requirements necessitated a waste disposal classification system. This classification system classifies waste sites in terms of (Ball and Bredenhann, 1992) :

a. waste type received
b. the size of the operation
c. the degree of leachate generation expected.

Using the Classification system and following the Integrated Environmental Management (IEM) Approach, Minimum Requirements are set and presented in a tabular matrix for each of the aspects under consideration. These minimum requirements will only become enforceable when included as permit conditions for a waste site.

The Directorates of Geohydrology and Water Quality Management (DWAF) are also involved in an investigation of groundwater protection principles and procedures. A policy on groundwater protection is envisaged in the future. This outstanding policy is urgently required - without the policy it is exceptionally difficult for governmental officials to know exactly how and what groundwater resources require protection.

3. RESEARCH METHOD

3.1. Initial Method Development

The research was carried out in a number of distinct phases. As a means of initiating the whole research programme, a site selection method was developed based on DRASTIC (Jolly and Parsons, 1991). The method was initially called DRASTICQUAD with Q being a water quality factor, U relating to groundwater usage in the vicinity of the waste facility and D relating to the distance of boreholes to the waste site. Software was developed that allowed for the easy recording of ratings and calculation of the index. Later the name was changed firstly to SSI (Site Suitability Index) and then to SGSI (Site Geohydrological Suitability Index). Even though the early method had a number of positive features, it still only yielded a relative score, was more suited to regional investigations and had not been verified using measured, field data. The methodology presented in this report supersedes these earlier efforts and is now called the Waste - Aquifer Separation Principle (WASP), which is the basic underlying principle of the method.

This methodology should not be confused with the Water Analysis Simulation Programme, which has also been abbreviated as WASP. The Water Analysis Simulation Programme is a surface water quality modelling tool described in more detail by Martin et al. (1991), Clark et al. (1989) and Warwick and Dannel (1989).

3.2. Literature Study

An extensive literature study was initiated as soon as funding for the research was approved. Site evaluation methods used elsewhere in the world (Appendix B) and the factors that impact on the suitability of a site for waste disposal formed the focus of this phase. This phase of the project was continued throughout the study and was only stopped just prior to preparing this research report.

3.3. Local Study Tour

During the initial stages of the project visits were made to a number of organisations involved in waste site selection and evaluation. As wide a range as possible of organizations were visited (Appendix A) in order that a good insight into the problems and issues involved in site assessment could be gained. The aim of the visits was to ascertain:

a. what formal methodologies were being used during site selection procedures in South Africa,
b. which factors were considered to be important in assessing site suitability, specifically in terms of the geohydrology,
c. identify sites suitable for more detailed investigation.

The study showed that limited use was made of any systematic methodology for waste site evaluation. Only three consulting organizations were aware of any methodologies, while most organizations paid scant attention to geohydrological investigations during waste site assessments. Valuable information was, however, collected on the factors and aspects which the various groups thought to be important in assessing possible groundwater impacts at waste sites.

3.4 International Study Tour

The initial phases of the investigation revolved around the collation of papers on existing site assessment methodologies throughout the world. During an American visit undertaken by Mr Reynders of the WRC he kindly collected reports and papers on research being carried out on the topic. European practice was not, however, well known and a study tour was undertaken. The aims of the European study tour were:

a. to obtain data on existing methodologies used in assessing groundwater pollution risk at waste sites,
b. to gauge opinions on the most important factors influencing groundwater vulnerability and pollution risk,
c. to find out about existing European legislation on groundwater protection and the siting of waste disposal sites.

Visits were made to government departments, research institutes and consulting organizations involved in waste disposal in England, Sweden, the Netherlands, Germany and Italy. A list of all the organizations visited during the trip are presented in Appendix A.

A number of different methods used in Europe or developed by Europeans were identified (Appendix B). Most of these methods were in-house assessment tools not used nationally or internationally. The awareness of risks to groundwater pollution was far greater in Europe than in South Africa, possibly because of the far greater role that groundwater plays in water supply (75 % in Europe as opposed to 13 % in South Africa). The major findings of the tour were presented in a report to the WRC (Jolly, 1992).

3.5. Methodology Development

Using the information gained from the literature study and the study tours, the type of method required was first identified. An important aspect in selecting the desired type of method was the characteristics of the method set out in the research objectives (Section 1.2.). The factors that had to be considered in the procedure were then selected. During the development process, numerous discussions were held with a broad spectrum of possible end users of the method (geohydrologists, pollution control officers, waste managers etc.) in order to ensure that the method satisfied the desired characteristics and applications. A paper was also presented at the Ground Water Division *Africa needs Ground Water* Conference held in September 1993 as a means of obtaining comment from the broader geohydrological community in South Africa (Parsons and Jolly, 1993).

3.6. Permit Data Collection

As a means of quantifying the nomograms used by WASP and hence calibrating the procedure, all reports submitted to DWAF as part of site permit applications were studied (Appendix C). It is, however, noted that not all of these sites were approved by DWAF. Information from a total of 106 waste sites were evaluated. All data considered by the method were recorded, as well as the estimated accuracy of the data. Five of the six regional DWAF Water Quality Management offices and Head Office were visited for this purpose.

3.7. Field Investigations

Field studies were initiated at 10 well studied waste disposal sites throughout the country (Appendix D). The purpose of this phase of the project was to verify the method using real data. The sites studied were selected using a number of criteria, including:

a. detail of previous investigation,
b. willingness of owners to co-operate,
c. wide range of geohydrological and waste conditions,
d. wide range of climatic conditions, and
e. perceived suitable and unsuitable sites.

Comment concerning the suitability of possible sites for study were sought from the project Steering Committee and from people visited during the local study tour. In order to ensure full co-operation from all parties and to ensure that the research was not hindered by activities and considerations outside of the objectives of the research, it was agreed not to identify the actual waste sites. This action was acceptable to the project Steering Committee. As a result, the waste facilities at which more detailed investigations were performed are referred to as Sites 1 to 10 (Appendix D).

All available data were collected for each site and studied. Sufficient data were available at four sites such that further field investigations were not necessary. Field work was then planned accordingly for the remaining waste facilities. Private drilling contractors were appointed by DWAF to carry out the drilling as Departmental rigs were involved in emergency drought relief drilling programmes. Fieldwork prior to drilling, drilling control and subsequent sampling was performed by CSIR and DWAF staff. Mr Sven Coles was sub-contracted by CSIR to perform drilling control at Queenstown. All water samples were analysed by Watertek's laboratory in Stellenbosch.

3.8. Data Analysis and Method Quantification

The permit application data were analysed using simple regression analysis, the results of which were used to quantify the nomographic solutions. The final nomographs were then refined based on the results of the field investigations. Even though every effort, within the constraints of the project, has been made to validate the method, it can be expected that some further refinements may be required after WASP has been used by the geohydrological and waste communities to evaluate both existing and new waste disposal facilities.

4. GEOLOGICALLY - BASED SITE EVALUATION METHODS

4.1. Methods Assessed

Following the Waterlit literature search, it became apparent that the volume of literature available on the subject of waste site selection and evaluation was immense. Additional relevant literature was also continually identified throughout the project. In order to make the task manageable and ensure that focus was kept on the development of a method, a number of decisions were taken with regard to the literature which could, within the time and budgetary constraints of the project, be evaluated:

a. vulnerability mapping approaches and techniques used, for example, by Parsons and Conrad (1994), Carter et al. (1987) and Goossens and Van Damme (1987), would largely be excluded from this study unless a specific contribution was made. This decision was based on the objectives of the research project which required that a method capable of site specific evaluation be developed. The only major exception to this was the inclusion of DRASTIC which was initially central to the project.

b. tools such as computer modelling of waste disposal sites (Hensel et al., 1991; Marin et al., 1989; Hobbs et al., 1988 and Gebhardt and Jankowski, 1987), the application of GIS (Aronoff, 1991; Brandt et al., 1989) and the use of Expert Systems (Murphy, 1990; Mak and Bot, 1987) would also largely be excluded from detailed study as:
   - the tools use methods in the assessment, but are not methods in themselves, and
   - the approach falls outside of the objectives of having easy-to-use methodology which does not require specialised skills.

c. approaches and methodologies used to assess the suitability of sites for nuclear and radioactive waste disposal (Gaynor, 1986; Hambelton-Jones et al., 1986) would also be excluded as such investigations are guided by strict international policy and standards (IAEA, 1977), are usually extremely detailed and do not use a formal method *per se*.

e. the procurement of additional literature would cease after August 1992.

These decisions were used for guidance purposes only. If literature was found which was unique or presented information of specific interest, then it was evaluated in detail. Where possible, cognisance was taken of the factors considered and trends presented in the literature which fell into the above categories.

4.2. Types of Methods

A total of 29 different waste site assessment and evaluation methods, which consider either geohydrological or broader earth science factors, were identified and appraised during this research effort. These are listed in Table 4 while short summaries of each are presented in Appendix B. Most of the methods were developed in either the USA or Europe, but application and use was found to be world-wide. The number of methods and approaches developed points to the universal nature of the problem of determining whether a site is suitable for waste disposal activities. Further, it indicates that the concept of standardization at a national or global level is either failing or is difficult to achieve.

Table 4: Site assessment methods evaluated during research project.

NAME	PRINCIPLE REFERENCE	TYPE
First Formal Evaluation	Dept. Water and Waste (1992)	matrix
Unlu *	Unlu et al., 1992	mathematical model
GSPW	Geological Sensitivity Project Workshop, 1991	numeric weighting and rating
MIRAMOS	Goosens, 1991	mathematical model
SINTACS	Civita et al., 1991	numeric weighting and rating
SSI	Jolly and Parsons, 1991	numeric weighting and rating
Cemeteries *	Hall and Hanbury, 1990	numeric weighting and rating
LPI	Meeks and Dean, 1990	mathematical equation
Vectorial Approach Method	Halfron, 1989	vectorial approach
HALO	Holmes, 1989	questionnaire
Al-Bakri *	Al-Bakri et al., 1988	mathematical model
Groundwater Pollution Risk Assessment	Foster and Hirata, 1988	graphical technique
DRASTIC	Aller et al., 1987, 1985	numeric weighting and rating
Chromatic Matrix Method	Andreottola et al., 1987	matrix
GOD	Foster, 1987	graphical technique
Survey	Kerkhof et al., 1987	questionnaire
Pesticide Index	Roa et al., 1985	mathematical equation
HELP	Schroeder et al., 1984	mathematical model
Intrinsic Suitability Flowchart	Shilepsky and Pulford, 1983	flowchart
Australian Le Grand	Kidd and Hancock, 1983	numeric weighting and rating
HRS	Caldwell et al., 1981	numeric weighting and rating
Brine Disposal Method	Western Michigan University, 1981	numeric weighting and rating using a flowchart
SRM	Kufs et al., 1980	numeric weighting and rating
Le Grand (1980)	Le Grand, 1980	numeric weighting and rating
SIA	Silka and Swearingen, 1978	numeric weighting and rating
Landfill Site Rating	Le Grand and Brown, 1977	numeric weighting and rating
Waste-Soil-Site Interaction Matrix	Phillips et al., 1977	matrix
SRS	Hagerty et al., 1973	numeric weighting and rating
Le Grand (1963)	Le Grand, 1963	numeric weighting and rating

* *no formal name given*

It is interesting to note the global trends in the formalisation of methods used to assess the suitability of a site for waste disposal. The problem was first brought to the fore by Le Grand in 1963 in America. His approach was fairly simple and based on five factors. He used a weighting and rating approach which has remained popular with many of the methods applying the same approach. Following the Love Canal saga in the mid-1970's, a host of methods were presented. These were mainly qualitative in nature, but based on more factors than Le Grand's earlier effort. Many of the approaches were aimed at identifying waste sites which posed a threat to water resources and hence required remedial actions. During the early 1980's, the limitations of the earlier attempts were exposed and new methods were proposed which addressed these limitations. Further, the new approaches tried to quantify the procedures by basing the methods on mathematical relationships. This resulted in more attention being paid to finer detail and the problem being addressed at a smaller scale. Le Grand was again prominent during this period. During the mid-1980's, attention was focused on regional planning needs. DRASTIC was developed such that areas vulnerable to contamination could be identified and hence restrict the establishment of waste facilities in these areas. DRASTIC was used, assessed and modified by a host of workers. Even after all the criticism levelled at it, it continues to form the basis of many of the more recently developed methods. At about the same time, Europe started to take note of the problem. This resulted in six methods being proposed in the literature within two years. The European methods were mainly qualitative in nature and were either numeric weighting and rating based, or used some form of graphical technique. The methods used groupings of factors in order that overall impact could be assessed ie. reverted back to larger scale assessments. In the early part of the 1990's, computer-based methods and tools received attention. Attention was also paid to specific waste problems such as those from the petroleum industry. Using similar techniques and approaches, the threat to groundwater resources posed by other anthropogenic activities was also considered. Standardised evaluation procedures were only really given consideration in South Africa during the early 1990's. The approaches proposed were, however, mainly literature based and were not verified in the field.

In comparing the various methods, it is found that a number of similarities exist, particularly in terms of objectives and factors considered. The modifications made seem to be related to specific site or area conditions, the nature of data available and the particular application. The basic philosophies employed have also not changed significantly. What has changed is the increase in the number of parameters considered and the use of computer-based tools to apply the method. The increase in the number of parameters considered reflects a more holistic approach to the problem and the desire or need for more detailed or smaller scale investigation. The employment of computer technologies should, in light of modern trends, be expected and allows for the management of large data sets and the faster execution of tasks.

In assessing the types of methods presented in the literature, two approaches were apparent. The methods could either be classified according to the procedure used to obtain some form of index or according to the purpose to which the result could be put. In the case of the former classification, the following types of methods were recognised:

a. numeric weighting and rating eg. DRASTIC
b. graphical technique eg. Groundwater Pollution Risk Assessment
c. flowchart eg. Intrinsic Suitability Flowchart
d. vectorial approach eg. Halfron method
e. matrix or tables eg. Chromatic Matrix Method
f. descriptive methods eg. Cartwright
g. questionnaire eg. Halo
h. mathematical equation eg. Pesticide Index
i. mathematical model eg. Unlu
j. combination of various types eg. Le Grand

The Geologic Sensitivity Project Workgroup (1991) presented a classification system based on the main function of the method. Most of the methods can, however, be used for a number of different applications:

a. selection of candidate waste disposal sites
b. prioritize existing sites for remediation
c. evaluate sensitivity over large areas
d. rank and evaluate individual contaminants according to pollution potential
e. evaluate candidate sites for Land Surface Treatment
f. evaluate pollution potential from oil and gas field activities
g. defining additional data requirements
h. defining engineering requirements
i. defining monitoring requirements

4.3. Selection of Type of Method to be Developed

In trying to identify the type of method to be developed, the research objectives had to be considered (Section 1.2.). The method had to be suitable for both screening and final site suitability assessment. It also had to be able to be used to define additional data requirements. Further, the method had to be in such a form that it would be easy to use and could be used by a wide range of people, some of whom may have limited geohydrological knowledge. Most of studied methods, and particularly the numeric weighting and rating methods, aimed to achieve the following:

a. provide at least a preliminary screening of site suitability or define the risk posed to groundwater resources by existing sites
b. use easily accessible or readily available data and information
c. provide a standard method or consistent approach to the problem
d. reduce investigation costs by maintaining focus

In order to achieve these, the methods had to use a number of simplifying assumptions. No single set recipe could be given for assessing the impact of waste disposal sites on groundwater, as the interaction between different factors is extremely complex. "Few universal rules or guidelines can be established because each disposal site represents a unique hydrogeological environment for which its design must be suited" (Cartwright, 1982, pp 197). Rather, the methods aimed to incorporate a general understanding of groundwater and contamination principles by means of a number of simplifying assumptions. A degree of flexibility is required for the method to have widespread application.

The limitations of the various types of methods, as well as the approach in general, also had to be considered before selecting the type of method to be developed. These included:

a. multi-purpose methods require too many generalities to be useful for local decision making,
b. many land-use decision makers want simple yes-no answers, the provision of which is certainly no easy task when dealing with such a complex environment and processes,
c. the siting of waste disposal facilities and the approval thereof is often a function of politics

and economics rather than physical, biological and chemical considerations, and

d. empirical assessment methodologies should be utilized for relative evaluations and not as absolute considerations of groundwater pollution - professional judgement must be used in the final assessment.

The most important reason for assessing the suitability of a site for waste disposal is to encourage and promote public and private land-use decisions, which will provide better long-term protection of water resources. Site assessments assist in planning, regulation, management and program implementation (Geologic Sensitivity Workgroup, 1991). Education is thus an important by-product of the development of site-specific methods as they allow non-experts to gain an understanding of the important factors examined during site assessment.

Equally significant to the objectives of the methods is the consideration of what the methods *do not aim to achieve*. Probably the most important is that the systems are not intended to replace the need for detailed fieldwork (Foster and Hirata, 1988; Aller et al., 1987). Vulnerability mapping, for example, may provide an overall or regional perspective, but site-specific conditions and considerations will ultimately determine a site's suitability. Such conditions can only be identified and quantified at the site of interest by means of appropriate field investigations and measurement.

After due consideration of the different types of methods, their associated advantages and disadvantages and the guidelines for developing an empirical site evaluation method (Canter et al., 1987), it was decided, in principle, that the numeric weighting and rating technique would be used. The main aim of using the technique was to promote repetitiveness in the final answer and to obtain some measure of quantification in WASP. However, once the factors to be used had been decided on (Section 6), it become clear that a combination of techniques would be more appropriate. As a result, WASP makes use of both questionnaire and nomogram approaches.

5. FACTOR IDENTIFICATION AND EVALUATION

5.1. Preamble

During the early stages of the project, it became apparent that the assessment of waste disposal sites, in terms of their potential impact on groundwater resources, had three distinct components which need to be considered. The components were initially divided on the basis of *source - path - sink* (Murphy, 1990) and this later crystallised into (Figure 1):

a. the *threat* posed by the waste pile,
b. the *barrier* between the waste pile and groundwater resources, and
c. the groundwater *resource*.

Many of the methods studied subscribed to similar concepts. Some applied the concept directly (Unlu et al., 1992; Foster and Hirata, 1988; Roa et al., 1985; Caldwell et al., 1981) while others consider it in a more indirect fashion (Holmes, 1989; Western Michigan University, 1981). One of the major differences between WASP and vulnerability mapping is, for example, that vulnerability mapping does not consider the actual threat posed. The fact that the zones were so distinct and easily differentiated between, in terms of both role played and actual physical boundaries, made this approach attractive. It was hence adopted as an underlying feature of WASP.

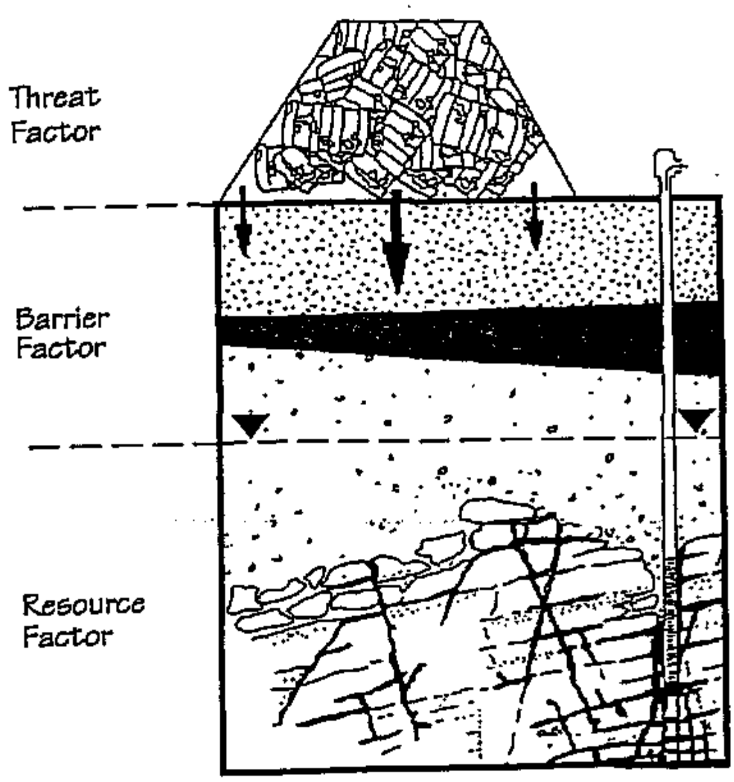


Figure 1: Factors impacting on the suitability of a site for waste disposal.

5.2. Threat Factor

The threat posed by a waste facility is essentially some product of the volume of leachate produced by the waste pile and the quality of that leachate. Both concepts are extremely difficult to predict with any certainty and need to be addressed separately.

5.2.1. Volume of leachate

Very little information are available concerning actual measured leachate production volumes at waste disposal sites (Parsons, 1994). As a result, the validity of tools developed to predict volumes of leachate generated at waste disposal sites remains in question. A large amount of work has been done in the field of leachate generation (Blight, 1992; Knox, 1991b; Farquhar, 1989; Hojem, 1989; Ham, 1988; Peyton and Schroeder, 1987; Ehrig, 1984). The factors which impact on the volume and rate of leachate generation are thus clearly identified in the literature. These include:

a. climatic conditions
b. moisture content of the discarded waste
c. moisture resulting from waste decompositions
d. hydrological and hydrogeological conditions of the site
e. properties of the waste
f. site design, operation and management
g. time

The classical waste site water balance (WSWB) method has long been used to predict the volume of leachate that could be generated. The method is based on the principle of conservation of mass and assumes that the system is closed. It is basically a budgeting approach. The mass of water entering the system must equal the mass of water leaving the system plus the mass of water retained in the system. The application of the method ranges from simple calculations to sophisticated computer models, the best known of which is the HELP model (Hydrological Evaluation of Landfill Performance). Following an evaluation of world literature available on the WSWB method, Parsons (1994) presented a list of serious short-comings of the method which resulted in it's validity in semi-arid areas being in question. Some of the more important limitations of the WSWB method include:

a. soil moisture budgeting techniques have been found to be invalid under arid conditions, with most of South Africa classified as a semi-arid area.
b. lack of reasonably accurately measured leachate generation data measured at actual waste sites against which estimations and predictions obtained using the WSWB can be verified and calibrated.
c. the approach is based on the assumption that field capacity has to be reached before leachate can be generated, while sufficient evidence exists that proves that this is in fact not the case.
d. the dynamics of the leachate generation process is not intrinsic to the procedure, particularly with regard to changing moisture conditions, changing rates of evapotranspiration losses, changing properties of the waste pile and arid zone hydrology.
e. owing to the very nature of the material and environment, the parameters required by the WSWB method are difficult to quantify with any certainty.

f. leachate generation (and recharge) is related to specific rainfall events and not seasonal and annual averages.

Parsons (1994) recommended that the use of the WSWB method to predict leachate generation be addressed and that, until the validity of HELP under South African conditions has been clearly established and verified, it should also not be used for this purpose.

In the same study, Parsons (1994) looked at groundwater recharge estimation techniquės with the view to applying recharge techniques for the estimation of leachate generation. He found that the approach proposed by Ham (1988) was similar to the empirical recharge estimation technique ie. a percentage of mean annual precipitation was assumed to either form leachate or enter the groundwater system as recharge. It was, however, found that the fundamental differences in the two processes (groundwater recharge calculation and leachate volume generation calculation) indicated that a direct comparison between the two was not legitimate. Further, because of the difference in scales involved in trying to predict output, the estimation techniques are not interchangeable.

In evaluating international trends regarding the quantification of the threat posed by waste disposal activities, it was found that the type and quality of waste was more commonly used than volumes of waste (Engelbrecht, 1993; Lisk, 1991; Foster and Hirata, 1988; NRPWM, 1986; Sumner, 1978). Excluding using some form of WSWB method as a basis for assessing risk (DWAF, 1994a; Farquhar, 1988; Shimmel, 1986), almost all methods rely on a qualitative approach or a "relative leachate production" indicator. This suggests that quantitative procedures are problematic and that, at this stage, a less accurate technique has to be accepted. The factors which can be used to define the threat include:

a. the population being served
b. the quantity of waste deposited over a specified time ie. load
c. the size of the landfill
d. the air space of the site
e. the expected life-span of the facility
f. generalised indicators such as *no risk, small risk, significant risk* etc.

A number of these classifications were studied by DWAF (1994a). Owing to the qualitative approach used internationally and in order to keep in line with the Minimum Requirements currently being developed for DWAF, it was decided in principle to adopt one of the classifications considered during the early stages of the Minimum Requirements project. DWAF (1994a) decided on using the *maximum rate of deposition* for their classification system. One of the major drawbacks of this approach is that the calculation of the maximum rate of depositions requires a number of parameters that are difficult to measure with any certainty (eg. population served, current rate of deposition). The calculation also requires an estimation of the rate of population growth, a parameter which has proved itself to be unreliable.

In selecting the most appropriate system to use for the purpose at hand, the following two criteria were considered:

a. a relatively static parameter was required eg. population could not be used because size changes continually.

b. a parameter that is relatively simple and accurate to measure was needed.

From this and in light of the fact that no proven method exists, it was decided that risk, in terms of leachate production, would be defined by the *designed final area* of the site, measured in hectares. It was recognised that the volume of waste pile could also have been used, but the measurement thereof is more difficult and expensive. The area data, on the other hand, is present in the permit application documentation and easily obtainable from maps and aerial photographs. Even though this approach has a number of limitations, it was regarded as the most suitable in terms of the objectives and desired characteristics of WASP.

5.2.2. Quality of leachate

Some form of waste type or chemistry is usually used to indicate the threat posed by the waste pile. As in the case of leachate production, quality can be grouped according to different criteria:

a. the source and origin of waste eg. domestic waste, mining waste, agricultural waste.
b. a list of substances in the waste, with associated degrees of risk attached to each substance.
c. a grouping of wastes according to chemical behaviour eg. flash point, spontaneous reactivity with air etc.

There appears to be little uniformity in the literature concerning this aspect. At present, waste types and the associated toxicity are being studied for DWAF by Fourie (1993). Engelbrecht (1993) assessed the health implications of leachate entering groundwater systems used for domestic supply. By definition, leachate is formed by water in a landfill which mobilizes contaminants from the buried refuse (Cartwright, 1982). It is thus reasonable to expect the nature or origin of the waste to be reflected in the quality of leachate that is formed. If the range of leachate qualities from domestic waste facilities reported in the literature are considered (Table 5), then it is clear that it is almost impossible to predict the quality of leachate from any given waste pile. Farquhar (1988) also found substantial differences in leachate chemistry of samples collected at waste sites of different ages. It is thus clear that waste type and leachate quality is difficult to use in a quantified manner to address the real risk that waste disposal poses to man and the environment.

To make the situation even more complex, some ions may be harmful to man, even at low concentrations but do not pose a threat to groundwater resources owing to their chemical properties and characteristics. For example, many metals pose significant risks to human health at concentrations of less than 1.0 mg/L (eg. Al, As, Cd, Cr, Cu, Ni, Se, Zn). The metals are insoluble under normal groundwater conditions and thus precipitate out of solution in the upper few centimetres of the vadose zone. As these ions require low pH conditions to remain in solution, the chances of re-mobilisation into solution as the landfill shifts towards methanogenic conditions are very slim. Other ions form compounds which are also insoluble under normal geohydrological conditions. A good example of this is Ca and SO_4 which precipitate out of solution as $CaSO_4$.

As in the case of the WSWB method, even though the processes and quantification of the problem are difficult to achieve, the general principles are accepted. A qualitative approach will thus also have to be used when trying to assign risk, based on the type of waste involved. If the types of wastes disposed of at municipal or commercial waste disposal sites are considered in terms of their generic

Table 5: Concentrations of leachate from domestic waste sites reported in the literature

Constituent (mg/L)	Young site [1]	Old site [1]	Acidic [2] phase	Methanogenic [2] phase	Leachate [3]	Contaminated [4] groundwater	Ranges [5] reported in UK	Ranges [6] reported in USA
pH	5.2	7.3	6.1	8.0	9.0	6.8	6.2 - 7.4	4.0 - 8.0
EC (mS/m)	1 970	180			1 260	1 900		
BOD	14 950		13 000	180			2 - 8 000	200 - 30 000
COD	22 650	81	22 000	3 000			66 - 11 600	1 000 - 90 000
DOC					330			
TOC						13.3	21 - 4 400	10 - 1 000
Na			1 350	1 350	2 216	140	43 - 2 500	100 - 1 500
K			1 100	1 100	703	27	20 - 650	100 - 3 000
Mg	277	81	470	180	206	36	12 - 480	200 - 1 000
Ca	2 136	254	1 200	1 200	13	185	165 - 1 150	100 - 3 000
Nitrate as N			3	3	nd	35	0.2 - 4.9	10 - 1 000
Ammonia as N			750	750	1	12	5 - 730	0.1 - 10
Organic N			600	600			nd - 155	1 - 1 000
Total P	7	5	6	6	1	1.7	nd - 3.4	300 - 3 000
Cl	742	197	2 100	2 100	3 333	243	70 - 2 777	10 - 1 000
SO_4			500	80	33	223	55 - 456	200 - 1 200
Alk			6 700	6 700	1 972	439		
As			0.160	0.160		0.109		
Cd			0.006	0.006		0.001	< 0.010	
Cr			0.300	0.300		0.025	< 0.140	
Cu	0.500	0.100	0.080	0.080		0.027	< 0.150	< 10
Fe	500.000	1.500	780.000	15.000	0.900	10.400	0.090 - 380.000	1.000 - 1 000.000
Mn	49.000		25.000	0.700		2.020	0.320 - 26.500	0.010 - 100.000
Ni			0.200	0.200		0.028	< 0.160	0.010 - 1.000
Pb			0.090	0.090		0.017	0.220	< 5.000
Zn	45.000	0.160	5.000	0.600		0.170	< 0.950	0.100 - 100.000

1 Cheremisinoff et al. (1984) 2 Ehrig (1984) 3 Leachate sampled at Site 2 4 Kerndorff et al. (1987) 5 Lisk (1991) 6 Driscoll (1986)

origin, then the following groups can be considered:

a. typical household domestic refuse
b. garden refuse and building rubble
c. commercial waste (mainly paper and the like)
d. industrial waste and effluent (solid and liquid)
e. medical waste

This list conforms quite closely to that currently used in the DWAF permit application form (DWAF, 1990). The moisture content of the different wastes should be considered. High moisture contents promote degradation and the mobilization of various chemical constituents at a faster rate than under dry conditions. High moisture contents also provide the mechanism with which the ions can be transported downwards through the waste pile and vadose zone into the groundwater body. It is accepted that waste with high moisture contents pose a greater risk, particularly in the short term, to groundwater resources. The DWAF permit application also has a *hazardous* category in which particularly toxic or noxious waste types can be grouped. Those wastes designated, for example, by the Hazardous Substances Act (Act No. 15 of 1973) as being in either Classes 3, 4, 5, 6, 8 or 9 would, for example, have to be disposed of in a particular manner at a site meeting certain specified physical and management requirements. DWAF (1994a) found it prudent to use two main classes of waste in their classification, namely *General Urban Solid Waste* and *Hazardous Waste*. Even though this categorisation appears valid for their purpose and moves away from the wide, and now confusing, usage of the prefix terms *Class* and *Group*, it was felt that the use of only two elements was too limited for the assignment of risk for WASP. The degree of detail proposed by DEA (1992) was, on the other hand, found to be too specialised for the task at hand.

As neither the local nor international literature provided a significantly better means of classifying the threat posed by different types of waste, it was decided that the approach used by DWAF would, in principle, be followed. The following waste classification was hence adopted:

a. garden and building rubble
b. domestic waste (including commercial waste)
c. dry industrial waste and domestic waste
d. liquid effluent and sludge and domestic waste
e. hazardous wastes (including medical wastes)

5.2.3. Underlying assumptions

It is important that the underlying assumptions of WASP be clearly identified in order that the limitations of the procedure can be understood and that should modifications need to be made during application, then such modifications can be made using a similar basis. The major underlying assumptions of the Threat factor are:

a. the risk posed by a waste facility to groundwater resources is directly proportional to the area covered by the site and the type of waste being disposed of.
b. the relative risk remains constant through geological time, irrespective of climate, site design and management practice.

Engineering aspects of waste management have been specifically excluded from this study. Much debate exists in the literature regarding the long-term effectiveness of site management in terms reducing the threat to groundwater resources. It is accepted that the adoption of modern landfilling practice reduces the impact of waste disposal on the environment. In light of the fact that liners and and site cappings have been proven to fail with time, it is assumed in this studyt that the *threat* to groundwater remains constant.

5.3. Barrier Factor

5.3.1. Preamble

Johnson (1991) states that the primary concern in selecting a waste site is the need for assurance that the waste will be isolated from freshwater zones for as long as the waste is hazardous to man and the environment. With this aim in mind, the basic underlying principle of WASP is that there must be an adequate barrier between the waste and any aquifers. The unsaturated zone forms the most important natural barrier between any waste site and the groundwater (Foster and Hirata, 1988; Foster, 1985; Matthess et al., 1985; Ross, 1985)

Often the type of barrier required below a waste site can be set as a legal requirement. As an example, the barrier underlying a French Class I "impermeable site" must have a hydraulic conductivity of at least 1 x 10^{-7} cm/sec and a thickness of at least 5 m (Barres et al., 1989).

5.3.2. Factors effecting the barrier potential

The ability of the unsaturated zone to act as a barrier to seepage of leachate into underlying aquifers is dictated by :

a. the hydraulic conductivity and porosity of the unsaturated zone,
b. the thickness of the unsaturated zone,
c. the attenuation potential of the soil and vadose horizons, and
d. the hydraulic gradient across the barrier.

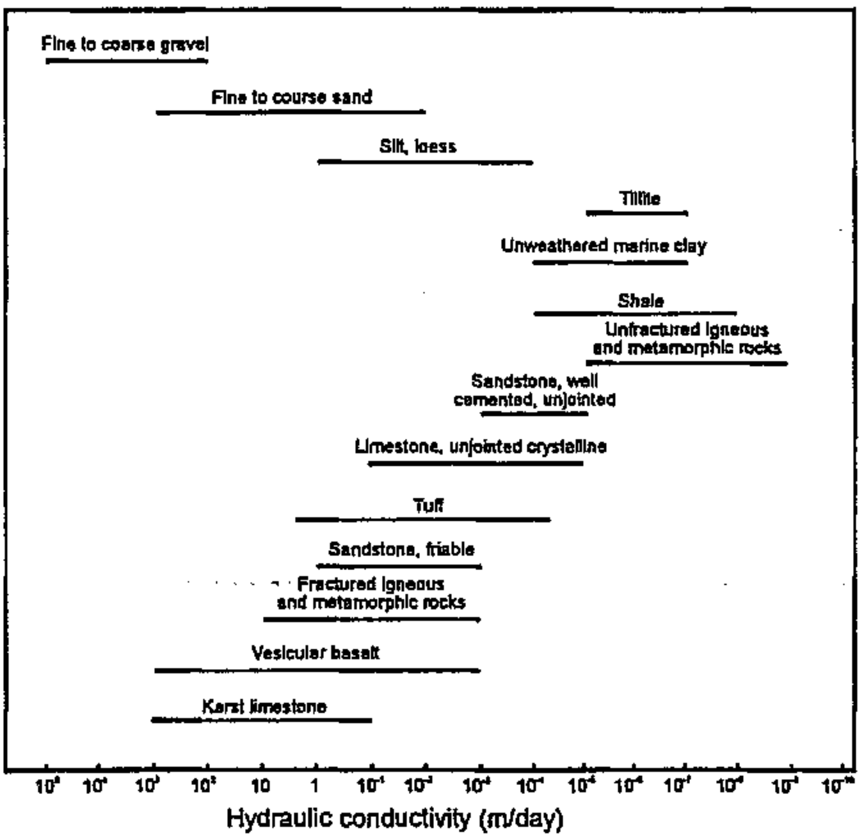
5.3.2.1. Hydraulic conductivity

The subsurface movement of potentially polluting substances is strongly influenced by the geological characteristics of the underlying strata and the related hydraulic conductivity, ie. the weathering, joints, dissolution channels and deep fracturing of clays (Shan and Stephens, 1993). This may be further increased by plant root holes and animal burrows. A range of some typical hydraulic conductivities for various geological units is presented in Figure 2. Presenting a more detailed range of values typical of South African aquifers is difficult, particularly owing to the largely fractured nature of local groundwater bodies. Such data should, however, become more freely available as the national and regional hydrogeological initiatives progress.

Flow in the unsaturated zone is complex. Flow rates are dictated by the moisture and gravity potentials of the horizon (Fetter, 1988). In an unsaturated horizon, moisture flows downward by gravity flow through interconnected pores and fractures that are filled with moisture. As the horizon becomes more saturated the soil suction is reduced and the rate of downward movement increases. Darcy's law is valid for flow in the unsaturated zone, although the unsaturated hydraulic conductivity is not a constant. The unsaturated hydraulic conductivity is usually lower than for a saturated zone of the same geology.

Most natural subsurface conditions are far from homogeneous, with zones of preferential flow occurring. The occurrence of these preferential pathways in a rock can be due to weathering, folding, faulting, fracturing or dissolution. Preferential flow pathways dictate the rate of subsurface flow of leachate. The development of preferential pathways can increase the hydraulic conductivity by up to four orders of magnitude (Driscoll, 1986).

Hydraulic conductivity (K) is also dependant on the chemistry of the fluid moving through the subsurface zone. Fernandez and Quigley (1985) showed that K for a specific formation can increase by up to five orders of magnitude when tests were undertaken comparing K determined using water to K determined using hydrocarbons (benzene, xylene and anilene). The lower the dielectric constant of the fluid (its ability to reduce the attraction between charged particles) the more permeable the fluid. The permeability of a barrier zone required below a waste site should take into account the lower dielectric constant of the leachate developed from a waste site. Since leachates differ between waste sites and over time at a specific waste site, it is impractical to undertake calculations incorporating dielectric constants and the quality of leachate.



(After Driscoll, 1986)

Figure 2 : Typical hydraulic conductivities for different lithological units

5.3.2.2. Porosity

The porosity (n) is defined as the "percentage of the rock or soil that is void of material" (Fetter, 1988, pp 63). There is a differentiation between primary and secondary porosity. Groundwater can be found in the voids between the grains in undeformed sedimentary rocks (primary porosity), or in the fractures and fault zones of deformed rocks (secondary porosity). The range of typical porosity of different lithologies is presented in Table 6. The range presented is typical of primary aquifers and secondary aquifers which owe their water-bearing properties to weathering processes. Fractured aquifers usually have storage coefficients and specific yields in the order of 1 % to 0.1 %. Even though these two parameters differ from porosity, they do indicate that the porosity of fractured aquifers can be much lower than the range presented in Table 6.

The greater the porosity the more space available for a leachate to be soaked up by the geological horizons and the greater the surface area for attenuation reactions to take place. Porosity changes have a limited effect on groundwater flow rates, because there is an inverse relationship between porosity and hydraulic conductivity which negates any flow variations.

Table 6: Porosity for common consolidated and unconsolidated materials

Unconsolidated Sediments	η (%)	Consolidated Rocks	η (%)
Clay	45–55	Sandstone	5–30
Silt	35–50	Limestone/dolomite (original & secondary porosity	1–20
Sand	25–40	Shale	0–10
Gravel	25–40	Fractured crystalline rock	0–10
Sand & gravel mixes	10–35	Vesicular basalt	10–50
Glacial till	10–25	Dense, solid rock	< 1

(Driscoll, 1986)

5.3.2.3. Vadose zone thickness

The thickness of material through which a contaminant must pass before reaching the groundwater (the barrier) is that thickness measured from the base of the waste pile to the top of the aquifer. It is important to ascertain whether the aquifer is unconfined or confined, or somewhere in between, as this would effect the calculation of the barrier thickness (Section 6.3).

In the past in South Africa, a 2 m unsaturated zone has long been used as a minimum requirement for the barrier below waste sites. Unfortunately this 2 m zone has been used without any consideration of the hydraulic conductivity of the geology resulting in sites being located on permeable sands overlying important primary aquifers where the water table is marginally deeper than 2 m. *The thickness of the unsaturated zone must be linked to the hydraulic conductivity of the geological horizons present.*

5.3.2.3 Attenuation mechanisms

As a leachate moves through the unsaturated zone, reactions take place which can improve the quality of the leachate. The material's ability to remove contaminants from the infiltrating leachate is known as attenuation (Johnson, 1981). Attenuation has an important role at waste sites, in that a barrier zone with a high attenuation potential will be more effective than a zone with low attenuation potential.

Attenuation is complex, with a number of processes being possible:

a. interception, sorption and elimination of pathogenic bacteria and viruses,
b. attenuation of heavy metals through precipitation, sorption or cation exchange,
c. sorption and biodegradation of many hydrocarbon and synthetic organic compounds (Foster and Hirata, 1991).

The soil zone is characterized by significant biological activity (Aller et al., 1987), which, coupled with high organic and clay levels, usually results in the soil horizon being a particularly important attenuation horizon. Most of the processes causing pollution elimination and attenuation occur at higher rates in the shallow soil horizon than at deeper levels (Robinson and Gronow, 1992). Often the soil horizon is removed during the development of a waste site. This should be discouraged owing to the value of soils in the attenuation process.

The most important geological characteristics for attenuation in the unsaturated zone are:

a. significant silt and clay composition (Heath and Lehr, 1987),
b. chemical composition (Cartwright et al., 1982),
c. high levels of iron hydroxides and lime, low soluble salts, medium texture and at least 20% clay content are the most suitable condition for attenuation (Robinson and Lucas, 1984).

In many situations the attenuation potential of the vadose zone is directly related to the residence time, in turn directly related to the hydraulic conductivity of the formation. Highly permeable rocks (fractured rocks) are totally unsuitable for the attenuation of leachate (Edworthy, 1989).

The attenuation potential of a specific geological formation is related to the chemistry of the pollutant. Some pollutants are highly persistent and are not easily attenuated. Furthermore the chemical attenuation potential of the unsaturated zone beneath a landfill is limited - at some stage conditions will become "saturated" and only limited attenuation will be possible. Biological attenuation is, however, still possible.

Some sites have been purposely designed as "attenuate and disperse" sites (DOE, 1986). Attenuate and disperse sites are sites which allow leachate to move from the landfill at such a rate that natural chemical and biological processes, coupled with physical processes such as absorption and dilution, have rendered such leachate innocuous by the time it reaches active or potentially active groundwater abstraction zones (Gray et al., 1974). This definition took into account that leachate would *not* have been fully attenuated by the time it reached the water table, so it was further recommended that any waste site should be at least 800 m from a groundwater source being used for supply. However, since any leachate is likely to be toxic, even in small quantities, waste sites should be kept away form potential water resources (Lee and Jones, 1991). Furthermore, Williams (1985) concluded that little reliance should be put on the unsaturated zone for attenuating organic components of leachate. This was also supported by Harris (1988) who stated that attenuation in the unsaturated zones is largely a myth as regards organic material. So even though attenuation of leachate does take place, it cannot be relied on as an aquifer protection procedure.

Attenuation also occurs within the groundwater body itself, with dispersion and dilution being two important mechanisms. These processes occur both laterally and vertically. For the purpose of WASP, only vertical attenuation in the barrier zone is considered.

5.3.3 Quantification of the Barrier Factor

The travel time for a leachate to penetrate the barrier has been used as the basis to define the Barrier Factor. Deeper water levels imply greater travel time, while a long travel time is indicative of a higher degree of aquifer protection in that more time is allowed for solute degradation, dilution and dispersion (Kalinski et al., 1993; Mather, 1989).

The travel time of a leachate through the saturated zone can be calculated from the following formula (Kalinski et al. 1993; Krapac et al., 1991):

$$Tt = \frac{d\,i}{[K\,/\,(n/100)]}$$

where	Tt	=	travel time (days),
	K	=	hydraulic conductivity (m/day)
	i	=	the hydraulic gradient
	n	=	porosity (%)
	d	=	barrier thickness (m)

Under conditions of vertical flow and when making approximations over long time periods, the hydraulic gradient can be assumed to be close to unity (Unlu et al., 1992), and thus can be disregarded in the calculation. If there is more than one horizon in the vadose zone, the travel time must be calculated for each horizon. The total travel time would be the summation of the travel times for all the horizons present.

The thickness of the unsaturated zone and the calculation of travel times is, however, made difficult by the occurrence of preferential pathways. Horton et al. (1987) tried to account for preferential flow conditions by using a reduced effective porosity in their travel time calculations. This approach is valid in South African conditions, particularly in light of the predominance of fractured aquifers and their associated low porosity.

Even though the concept of using travel time to quantify the effectiveness of the vadose zone to act as a barrier is simplistic, the concept has been shown to be valid. Peters (1993), for example, reported that the influence of leachate emanating from a 25 year old landfill was restricted to the upper 5 cm in the soil below a waste site. He ascribed this to chemical retardation by the bedrock. However, if the parameter values presented by Peters ($d = 0.05$ m and $K = 1x10^{-6}$ m/d) and an assumed porosity of 30 % (typical of clay) are used to calculated a travel time, a 41 year travel time is estimated. From this, it can be argued that the reason that leachate is only detected in the upper 5 cm of soil is because that is the distance travelled in the given time. The lower concentrations recorded beneath 5 cm is not a result of attenuation, but rather because the leachate has not yet infiltrated to that depth.

5.3.4. Underlying assumptions

a. The lower the hydraulic conductivity and the higher the porosity of the unsaturated zone, the greater the ability of the natural barrier zone to reduce any threat to underlying aquifers because of greater leachate containment and attenuation potential.

b. Although hydraulic conductivity (K) values vary dependant on the chemistry of the permeating fluid, K values should be determined using water as the fluid

c. Thickness of the vadose zone is defined as the depth to static water level for unconfined aquifers and depth to piezometric surface for semi-confined and semi-unconfined aquifers. Only in the case of a clearly definable confining layer is the first water strike used to define the thickness of the barrier zone. Any assessment of the nature of the aquifer should err on the conservative side. The use of depth to water to define barrier thickness removes the difficulties associated with preferential pathways in secondary aquifers.

d. Flow is assumed to adhere to Darcy's Law.

5.4. Resource Factor

5.4.1. Preamble

The difference in geohydrology associated with water supply and geohydrology associated with siting waste disposal sites is that, in the case of the latter, low permeability geologic environments are appraised, compared to higher permeability conditions associated with aquifers. Cartwright (1982) referred to this as *antihydrology*. One of the difficulties associated with the evaluation of groundwater resource potential during site suitability assessments is that vague terms, which cannot be physically measured, are used in the definition of aquifers. Freeze and Cherry (1979) note that, of all the words in the hydrologic vocabulary, there are none with more shades of meaning than the term *aquifer*. It means different things to different people, and perhaps different things to the same person at different times. A number of definitions are presented in standard geohydrological text, but most include concepts such as *yield sufficiently large amounts of water*, *water-bearing formations* and *economic importance*. Kruseman and De Ridder (1991, pp. 13) define an *aquifer* as:

> *a saturated permeable geological unit that is permeable enough to yield economic quantities of water to wells.*

The identification of aquitards could probably be more appropriate to the waste management field. An *aquitard* is defined as (Freeze and Cherry, 1979, pp. 47):

> *a saturated geologic unit that is incapable of transmitting sufficient quantities of water under ordinary hydraulic gradients.*

The imprecise definitions suggest that the task of quantifying the resource factor will be complex because of the large number of variables which impact on the value of a groundwater resource to potential user. Further, no simple measure of geologic sensitivity to contamination exist. It was also noted that the more complex the methodology developed in this study, the more difficult and expensive it will be to obtain all the required data. Some simplifications and generalizations are therefore unavoidable. In looking at groundwater resources in terms of waste disposal, the aim is to define the nature and magnitude of the resource which could be compromised should contamination occur.

5.4.2. Groundwater quality management policy

In trying to assess the value of groundwater, it is neccessary to evaluate current initiatives regarding groundwater management policy and strategy in South Africa. "Groundwater is a strategic resource, being the sole or main source of water supply in the drier two thirds of the country" (DWAF, 1992, pp.3). The resource must therefore be thought of in terms of its strategic value. Consequently, special attention must be paid to smaller communities where groundwater is, in relative terms, a very important resource. During the evaluation of existing permit applications, it became apparent that 75 % of waste sites in South Africa have a size of less than 30 ha (Section 6.2.). It is probably these facilities which pose the greatest risk to groundwater resources owing to:

a. the strategic importance of groundwater to these communities,
b. the limited resources available to these communities which hinders the adoption of sound waste management practices, and
c. the limited expertise available to water supply managers and waste managers of the smaller towns and villages.

DWAF (1992) reviewed groundwater quality management strategies and policies to be adopted in South Africa (Section 2.2). The *precautionary approach* and a policy of *differentiated protection* were probably the two most important features of the document. Coupled to this, DWAF (1991) adopted some aspects of the *principle of anticipatory environmental protection*. These three principles provided a clear direction of current water quality management policy and are hence subscribed to by WASP.

The precautionary approach is merely the adoption of conservative policy and practice in order to counter current limits of our knowledge and a change in acceptable standards over time. The highest level of protection should therefore be afforded in order to avert danger and minimize risk to groundwater resources. The special characteristics of groundwater make this a particularly apt approach to employ. These characteristics include:

a. groundwater has no assimilative capacity
b. the impacts of pollution are often only detected long after the event
c. contamination is invisible and difficult to monitor
d. restoration is expensive, if not technically impossible.

Three different protection policies were evaluated by DWAF (1992). A *non-degradation* policy may be the most desirable from an environmental protection point of view and can safeguard against a lack of knowledge, but it would also be almost impossible to implement and extremely expensive. A policy of *limited degradation* allows for contamination up to certain standards. The approach is reactive in nature and the special characteristics of groundwater make this policy difficult to achieve. The extensive scientific analysis needed to provide the necessary management information would also make this a costly policy to adopt. A policy of *differentiated protection*, even though it has some weaknesses, was regarded to be the most realistic policy to adopt. It, in fact, presents a compromise between what is desirable and what is feasible. The policy signifies that all viable aquifers have to be protected to a high level, irrespective of whether they are being used or not. Certain remote aquifers and aquitards require a much lower level of protection. The adoption and application of the policy, however, requires information on which to base decision making. Such information is often based on some form of standardised classification and is presented on various types of maps.

Skinner (*pers. comm.*, 1993) maintained that differentiated protection is not a groundwater protection policy *per se*, but rather a practical procedure to be implemented under a policy of non- or limited degradation.

The *principle of anticipatory environmental protection* encompasses all positive actions to avert danger or minimise risk to the environment. The objective is not simply to avoid problems, but to plan in order to gain environmental and economic benefits from all opportunities. Preference is given to controlling the cause of pollution rather than treating the symptoms of it.

5.4.3. Aquifer classification

The aim of an aquifer classification is to group various geohydrologic units according to certain criteria in order that:

a. potential groundwater resources can be identified,
b. the value of the resources can be ascertained,
c. groundwater utilisation can be described,
d. guidelines for land-use zoning can be presented,
e. aquifer vulnerability can be demarcated, and
f. potential pollution sources can be delimited.

Aquifer classification systems are presented by Jolly and Reynders (1993) and USEPA (1985). Geohydrological and vulnerability mapping can also be regarded as a form of aquifer classification and the current national hydrogeological mapping initiative will lead to some form of nationally consistent classification. One of the drawbacks of classification systems, in terms of this research, is that they tend to be more suited to regional and national scale application. A number of generalisations and simplifications are required and detail is lost through the small scale. The resultant classification is often based on broad groupings such as *sole source aquifers*, *principal aquifers*, *important aquifers*, *minor aquifers* and *insignificant aquifers*. The use of such classifications for a particular purpose still requires some form of professional judgement.

It was felt that the aquifer classification approach, undertaken on a regional scale, was too general for the assessment of the impact of waste disposal activities on groundwater resources, undertaken on a local scale. A more dynamic system was required which covered most of the factors and considerations of concern. The method of assessing the Resource Factor had to clearly distinguish between an aquifer (in relation to its current or potential users) and groundwater bodies or aquitards of limited potential for development.

5.4.4. Factors used to quantify the Resource Factor

When trying to quantify the value and importance of a groundwater body in a single numeric value, one is essentially trying to summarise the science of hydrogeology into a short paragraph. The measurable individual factors and parameters are fairly meaningless in themselves, but rather have to be evaluated holistically. The following information needs were recognised:

a. geology
b. hydraulic parameters
c. water quality
d. water abstraction and usage patterns in terms of population and land-use
e. potential contamination sources and characteristics

5.4.4.1. Geology

The geology of an area usually gives some indication of geohydrological potential. Aquifers can be sub-divided into primary and secondary aquifers, with approximately 95 % of South Africa's aquifers being of the secondary type. Secondary aquifers are usually characterised by low storage coefficients, complex hydraulics and flow occurring along preferential paths. Degree of weathering, degree of fracturing and the presence of intrusive rocks all give some indication of the water-bearing potential of a particular hard rock formation. The geohydrological capabilities of most of South Africa's major lithological units are fairly well understood, at least on a qualitative basis. The dolomites of the Transvaal Sequence and the quartzites of the Table Mountain Group are regarded as having good geohydrological capabilities. Shales of the Malmesbury Group and Bokkeveld Group, on the other hand, are regarded as having much lower water-bearing capacity. As the national mapping initiative proceeds, more qualified information on the geohydrological characteristics of the various lithologies and stratigraphies will become available.

5.4.4.2. Hydraulic parameters

These include measurable parameters such as borehole yield, aquifer yield, hydraulic conductivity, transmissivity and storage. Even though they can be measured relatively accurately, they can be quite misleading if considered incorrectly. The yield of a borehole is probably the most misused of all geohydrological considerations. Yield can vary considerably over short distances when dealing with fractured rock environments. It is not uncommon in these environments to have two boreholes located within close proximity of each other with yields of different orders of magnitude. Borehole yield is usually a function of proper siting, borehole construction and appropriate pumping practice.

To use borehole yield as a means of classification is also dangerous, as the value of yield varies considerably throughout the country. The weathered aquifers of the Halfway House Granites have, for example, one of the highest density of production boreholes in use in the country (Johnstone, *pers. comm.*, 1993), yet most measured sustainable yields are less than 2 L/s. Rather, the ability of an aquifer to yield sufficient quantities of water to meet the water demand of a community and the manner in which it can be used by that community should be considered. Some examples include:

a. if a borehole yielding 0.5 L/s is used by a single farmer as his sole source of domestic supply, then this should be regarded as a supply of strategic and economic significance.

b. if twenty boreholes equipped with hand pumps capable of pumping 0.1 L/s are used to supply a rural village with water, then the geologic unit from which the water is abstracted must be regarded as an aquifer.

c. if 5 production boreholes have to be developed in order to supply a small town with a water supply of 5 L/s, then this resource also has value.

d. a single borehole with a yield of 30 L/s may not have much significance in terms of the total demand of a major metropolitan area, but such a borehole could be of great importance in terms of peak water demand, reticulation management and drought relief. The current trend of the municipalities of Midrand, Verwoerdburg and Pretoria to augment surface supplies with groundwater is a good example of how relatively small volumes of groundwater can be beneficially used.

It was interesting to note that at the recent International Association of Hydrogeologists (IAH) conference held in Norway, those geologic units that yield sufficient water to supply a family of five with potable water were regarded as aquifers (Weaver, *pers.comm.*, 1993). This equates to a borehole yield of approximately 0.01 L/s.

The parameters which define water transmitting capabilities (permeability, hydraulic conductivity, transmissivity) and storage capacities (storage coefficient, specific yield) can be used to determine flow rates and the like, but *unless these parameters are considered in terms of aquifer yield in relation to the user, or potential user,* they have little value in quantifying the Resource Factor.

5.4.4.3. Water quality

Water quality is as important as quantity. One of the advantages of using groundwater in South Africa is that little water treatment is required. This reduces water supply running costs. Natural quality can vary considerably and is usually controlled by geological conditions. The quality of groundwater abstracted from the coastal primary aquifers, the dolomitic aquifers and the quartzitic aquifers is good with electrical conductivity (EC) generally being less than 100 mS/m. Water from the Karoo Supergroup aquifers is usually not of the same good quality but is still potable. Shales of the Malmesbury and Uitenhage Groups often yield very poor quality water not fit for human consumption. Bredenkamp et al. (1991) noted that there is a general decline in groundwater quality from east to west across the country and ascribed this to climatic conditions.

Until recently, general water quality guidelines set out in SABS 241 - 1984 (SABS, 1984) were used to evaluate the suitability of water for domestic use. This has now been replaced by more rational and risk-based guidelines which relate the required quality to *fitness-for-use* by a particular water user (DWAF, 1993). Four uses are currently recognised (domestic, recreational, industrial and agricultural) while quality guidelines for the natural environment and the coastal and marine environments are also being considered.

5.4.4.4. Water abstraction and usage

The strategic value of a resource is measured by its current usage and its potential to be used. Groundwater has long been regarded as the Cinderella of South Africa's water (Wright, 1993). The use of the resource for domestic supply is, however, becoming more of the norm as the cost of surface water resource development increases and as the country starts reaching it's natural resource limits

(Section 2.1.). The usage of dolomitic groundwater by the municipalities of Midrand, Verwoerdburg and Pretoria is again a good example of this trend. Possible usage of a water resource in the future must hence also be considered.

In considering usage and potential usage, real users must be identified. An aquifer located near a town has a greater chance of being used than an aquifer located some distance away from a town. As in Sections 5.4.4.2. and 5.4.4.3., the resource has to be considered in terms of the user and the usage. Those aquifers used as sole source aquifers are hence regarded as more important than those that are used conjunctively, or for water supply management purposes. It is, however, not possible to consider usage and user aspects in measurable terms, as a number of inter-related aspects are of relevance:

a. population size,
b. long-term yield matched against current and potential future demand,
c. percentage of groundwater used to meet demand,
d. economic value of resource, cost of resource development and cost of alternative resource development,
e. drought relief and water supply management,
f. distance between production holes and contamination source,
g. competition for resource amongst different users, and
h. risk of contamination.

The technique used to quantify the Resource Factor had to be capable of including all of these considerations in the assessment.

5.4.4.5. Potential contamination sources

The existing contamination and the risk of contamination to a resource have serious ramifications with respect to the viability of a resource being developed for water supply purposes. An aquifer overlain by an area with limited development faces a far smaller risk of contamination than an aquifer underlying an urban environment. The threat of contamination can reduce the strategic value of the resource. Parts of the dolomitic aquifers are, for example, located near major urban and mining areas and the threat of significant contamination to these vulnerable aquifers has to be considered when assessing the feasibility of developing the dolomitic aquifers as major sources of drinking water.

5.4.5. Basis for quantification

Because of the large number of geohydrological variables that have to be considered in determining a Resource Factor, neither the empirical relationship used to quantify the Threat Factor (Section 5.2) nor the mathematical relationship used to define travel time in the vadose zone, and hence the Barrier Factor (Section 5.3.), could be used. After due consideration was given to approaches employed by the other methods studied, it was decided that a questionnaire approach using *yes* and *no* type answers would best be suited for the task at hand. The questionnaire was to be structured in such a way that the difference between "used" resources and "potential" resources could be considered. Both were to be considered in terms of the existing or potential users.

Even though this technique is fairly qualitative in nature, it does allow for the answers to be based on varying degrees of detail. The following example is used to illustrate this. One of the questions to be answered is:

is the groundwater quality such that it is fit - for - use by the potential users?

In the planning stage of the siting, information gained from groundwater quality maps or reports dealing with groundwater exploration on a regional scale could be used to answer this question. A more detailed level of investigation would require that the answer be based on information obtained during a groundwater sampling exercise in the area of concern. In some instances, it may be required that boreholes be drilled specifically to investigate groundwater quality in the immediate vicinity of the planned waste disposal site. More discussion about the detail of information used by WASP is presented in Section 5.5.

5.4.6. Underlying assumptions

The following assumptions are inherent to the quantification of the Resource Factor:

a. all groundwater bodies have some intrinsic strategic value which can be quantified in terms of usage and potential,
b. the precautionary approach and differentiated protection policy are the most suited policy for South African conditions, and
c. the treatment and purification of contaminated groundwater is not a feasible long-term water supply strategy.

5.5. Quality of Data Used During WASP Application

An area that required some attention was that of the detail of information required when assessing the suitability of a site based on geohydrological criteria. As groundwater is an intangible resource that cannot be seen, the only means of collecting geohydrological data is by drilling boreholes or through indirect means such as geophysical techniques. Indirect techniques still, however, require some form of calibration. The collection of geohydrological information is consequently relatively costly. The setting of data and information requirements thus has significant economic implications.

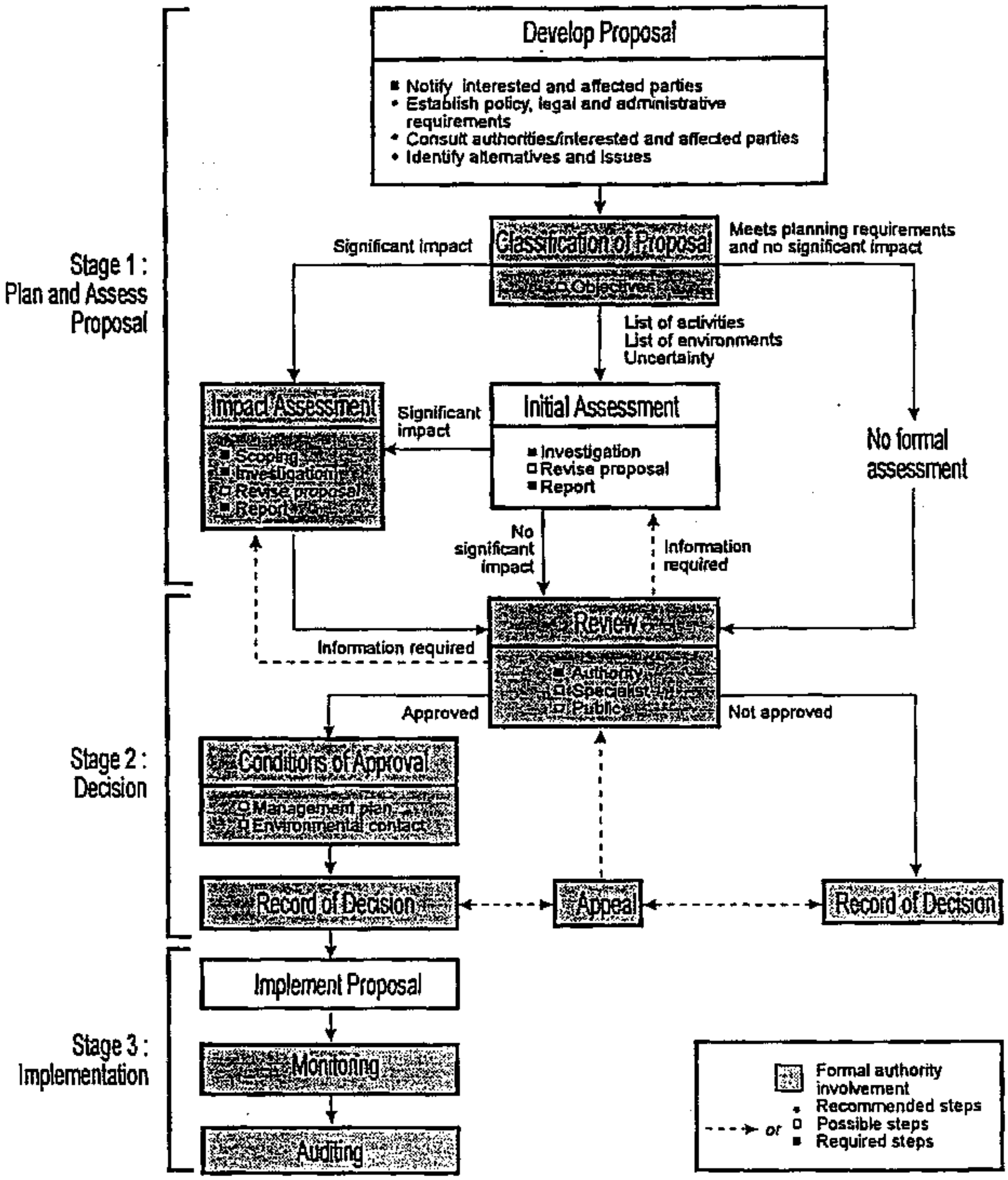
Initially, it was proposed that the application of WASP be contemplated in terms of 3 or 4 levels of investigation, similar to those proposed by Ninham Shand (1993), the Geological Sensitivity Project Workgroup (1991) and Avendt (1988). On further investigation, it was postulated that this approach could require different models to match each level of study. Consideration of the Integrated Environmental Management (IEM) procedure, diagrammatically presented in Figure 3, showed that one model could be used if the amount and quality of data and information was appraised.

The evaluation of information contained in the DWAF permit application documentation showed a wide range in terms of the amount of data recorded and the quality of information presented (Section 6). It was decided that the concept of data reliability would be used and that the concept would conform to the principles of IEM. A data reliability rating would be assigned to each Factor and a composite score would be recorded with the WASP rating. Three reliability levels were set:

data reliability 1:	based on detailed study and accurate measurement, the system can be well described and the user of WASP is certain of the information presented.
data reliability 2:	based on partial studies
data reliability 3:	assessment is based on limited data, knowledged based on experience elsewhere and uncertainty regarding various aspects of the assessment exists.

Level 1 would conform to a detailed *impact assessment* of the IEM procedure while levels 2 and 3 would equate to an *initial assessment* and *no formal assessment* respectively. Even though the data reliability rating is fairly qualitative and flexible, it does give a reasonable indication on the quality and quantity of data used in the WASP assessment. A data reliability rating of 1.3 would, for example, indicate that essentially detailed data were used. A rating of 2.6 points to the use of limited data and that the assessor had to largely rely on his judgement and experience in performing the WASP assessment.

The data reliability concept promotes a phased approach to the problem of site selection and assessment. A data reliability 3 level assessment could, for example, be used to identify and rank potential new waste disposal facilities while a level 2 investigation could be used to assess the site with the most potential. From this level of work, DWAF could be approached regarding the issuing of a permit. DWAF may accept the presented information or may request additional data. A Class 1 facility would always require detailed study and DWAF would hence specify a data reliability 1 requirement be met before a permit could be issued.



(After DEA, 1992b)

Figure 3: The IEM procedure

6. DEVELOPMENT OF WASP

6.1. Introduction

It was never intended that WASP replace the need for appropriate field study (Section 1.2.). The degree to which any given situation can be assessed depends on the available information and the expertise and experience of the person doing the assessment. Even though every effort has been made to ensure that WASP is accurate and reliable, the underlying assumptions and the model itself cannot be applicable to all possible situations. It is therefore the responsibility of the user to ensure that the application of WASP is appropriate and that the result obtained is a true reflection of the situation being investigated. Even though WASP can be used by most people to gain some understanding and knowledge of the factors that need to be considered, the type of data required and the possible suitability of a particular site, it is required that the final assessment be performed by a person knowledgable and experienced in the field of geohydrology. It was felt prudent that a precautionary statement be included in the front of the manual to alert users to these considerations.

GENERAL PRECAUTIONARY STATEMENT

The quality of an assessment and the accuracy of the results are directly related to the technical capability of the user and the amount and quality of available hydrogeologic information. The degree of reliability achieved by anyone using WASP depends on their level of training and on the amount of information available to determine hydrogeologic conditions. The application of WASP requires experience in interpreting subsurface geologic and groundwater information to produce satisfactory results. It is thus required that only persons of suitable training and experience in the field of geohydrology perform the WASP assessment which will be used to make decisions regarding the suitability of a particular site for waste disposal activities.

Further, it is recognised that this method cannot be suitable for all situations. Even though every effort has been made to develop a systematic and objective methodology, which accurately defines the physical environment, the onus remains with the investigator to ensure site suitability.

Adapted from Geologic Sensitivity Project Workgroup (1991, p. 17)

6.2. Threat Factor

The quantification of the Threat Factor proved to be extremely difficult as the approach was essentially qualitative in nature and little information based on actual measured data were available. As the risk was regarded as a relative indicator, it was decided to examine all the data collected from the permit application forms and reports.

The range of designed final area of waste disposal facilities encountered is recorded in Figure 4. The large majority of sites are smaller than 30 ha, with only the larger towns and cities having sites larger than this. Only one site had a designed final area of greater than 100 ha, but it would appear that an emerging trend is to have a fewer number of larger sites than a large number of smaller sites ie. regional sites are becoming more popular. In terms of the reliability of the data, it was found that 75 % of the information was rated as level 1 data, 22 % as level 2 data and only 3 % as level 3 data (Figure 5).

Based on the classification presented in Section 5.2.1, it was established that almost all of the sites examined accepted domestic waste (Figure 6). Only one site was used exclusively for the disposal of garden and building rubble while a total of 8 hazardous or Class 1 sites were investigated. Co-disposal of industrial effluent and sludge with domestic waste took place at 7 of the sites, while the co-disposal of domestic wastes with wastes from a higher risk group was common. The reliability of this data was high with 95 % of the data being found to be level 1 data while no level 3 data was recorded (Figure 7). Uncertainty arose in only 4 cases and related to defining the waste as being either dry industrial waste or liquid effluent.

In trying to provide a reasonably accurate relative indication of risk that a waste pile poses to a groundwater resource, two questions had to be posed:

a. With all other factors being equal, what would the difference in relative risk be between two sites differing in size?

b. With all other factors being equal, what would the difference in relative risk be between two sites which accept different types of waste?

Based on an iterative process which considered information available in the literature, the information obtained from the permit application data, discussions with various waste managers and observations in the field, a nomogram was compiled from which the Threat Factor could be determined (Figure 8). The lines in this graph are somewhat subjective in that the curvatures have been used to allow for the adoption of a conservative approach.

Using this diagram, a site with a designed final area of 1 ha, which accepts only domestic waste, would have a Threat Factor score of just over 3, while a site covering 20 ha would have a Threat Factor score of 5.5. A large regional site of 100 ha would have a score of 7.2. Similarly, a site of 1 ha which accepts dry industrial waste would have a rating of 4.5 while a similar sized site, which accepts liquid waste, would have a rating of 6.1. A Class I landfill, with a final size of 1 ha would have a Threat Factor rating of 8.

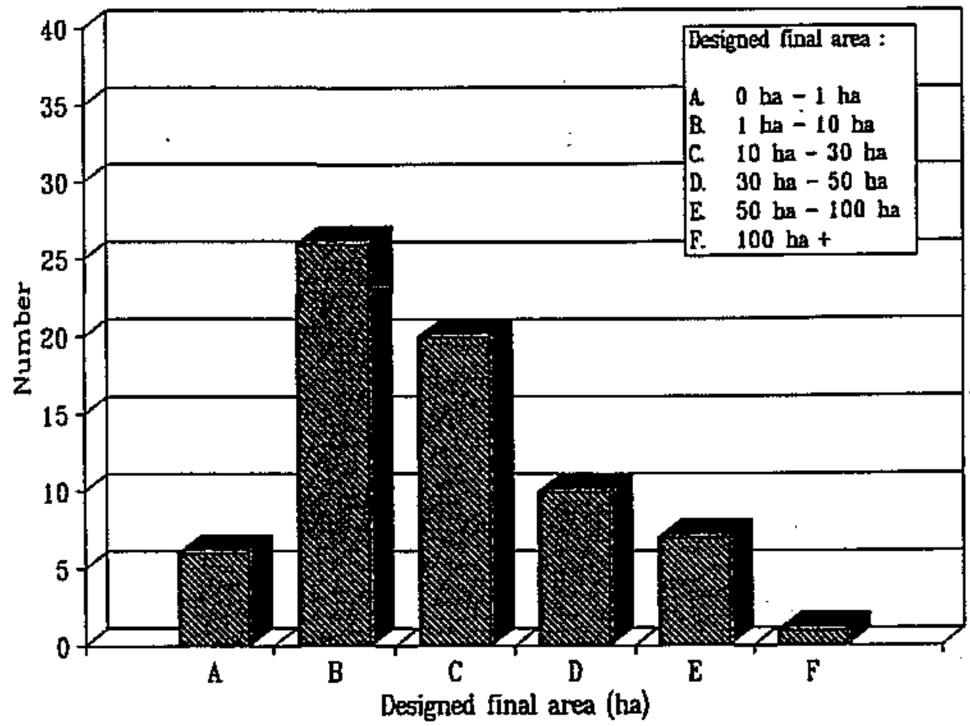


Figure 4: Range of designed final area of waste sites.

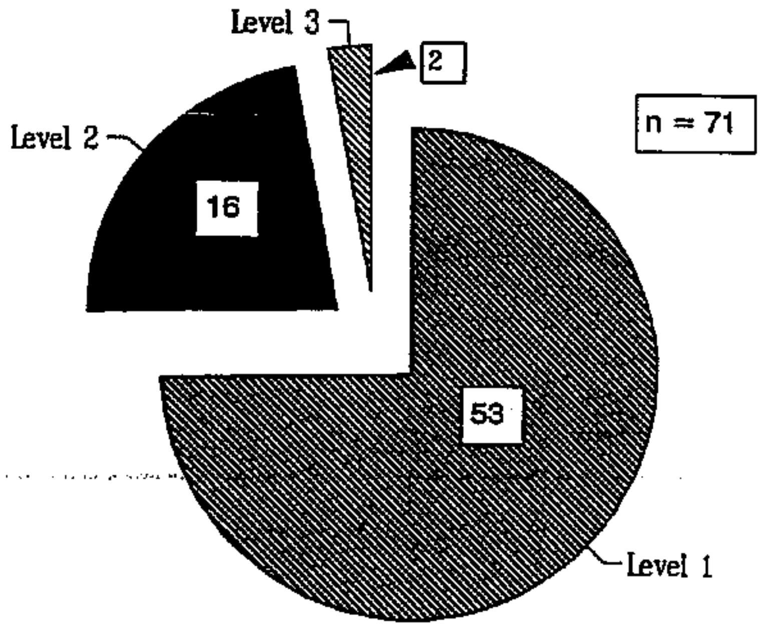


Figure 5: Reliability of designed final area data

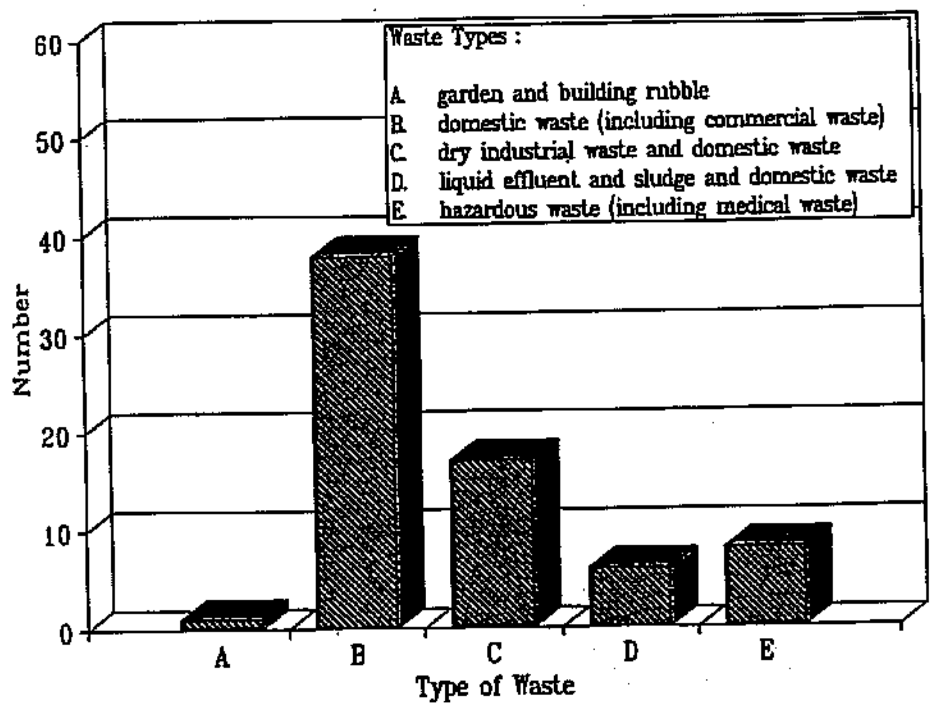


Figure 6: Graph showing the spread of the different type of waste used in the quantification of WASP.

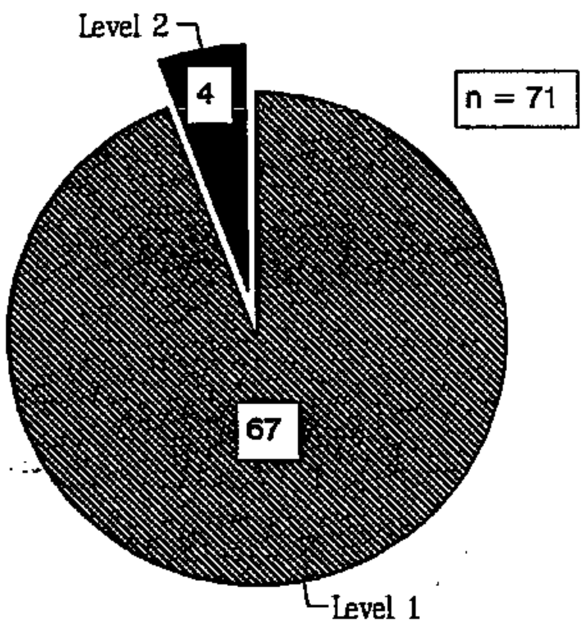


Figure 7: Reliability of waste type data

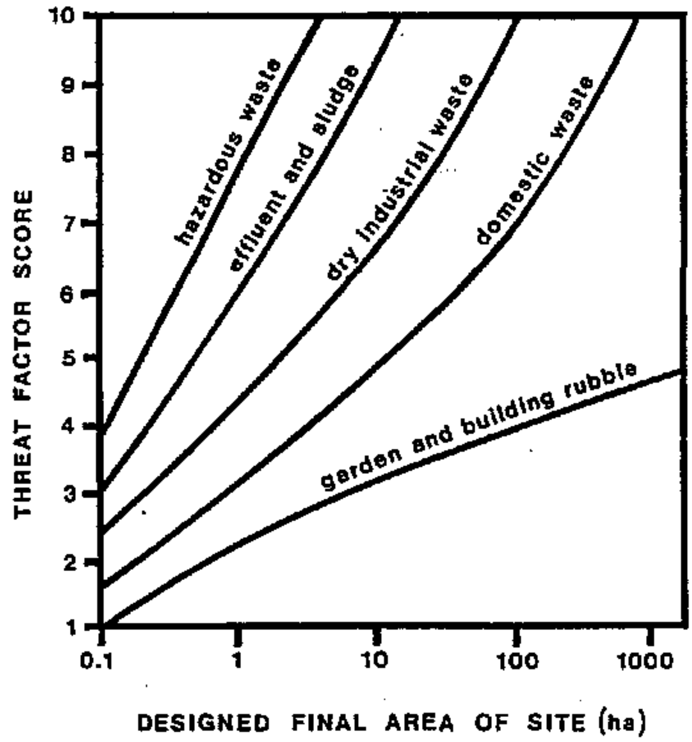


Figure 8: Threat Factor nomogram.

The data reliability scale of the Threat Factor components are presented in Table 7. The reliability of each component is rated according to the scale and an average of the two obtained and recorded. The Threat Factor data reliability rating is then included into the final data reliability rating.

Table 7: Scales for rating the data reliability of the Threat Factor

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Size of site	certain - based on site field measurement or approved final site plan.	based on aerial photograph or map measurements and estimations.	uncertain - based on estimations.
Waste type	certain - based on observed and monitored waste deposed.	based on extrapolated information from similar situations.	uncertain - based on estimations.

6.3. Barrier Factor

It was motivated in Section 5.3. that the travel time required for leachate to pass through the vadose zone was a good measure of the ability of the barrier zone to separate waste from an aquifer. The formula presented in Section 5.3. is used to calculate travel time.

The ability of the barrier to limit throughflow is controlled by the most permeable flow path. *The hydraulic conductivity which should be used in WASP must be the highest hydraulic conductivity measured during field investigations and not an average.* The range of K presented in the permit application data is presented in Figure 9 while the reliability of the data is recorded in Figure 10. It is clear that sites have been located at sites with very wide ranging K values. The fact that 27 of the 71 sites studied are located on formations with K ranging between 0.1 to 100 m/d is a cause for major concern. It is important, however, to note that, historically, such data was not requested.

Almost no measured porosity data was recorded in the permit application data (Figure 11). This is not surprising, as such data has never been requested in the permitting process. Further it is not usually of great significance in hydrogeological studies. Storage coefficient and specific yield are of greater interest in terms of void space. It was considered at one stage to calculate a barrier index using only thickness and K, but it was decided that porosity would continue to be used since a Barrier Index would have little practical meaning while the travel time concept was a tangible one. Small changes in porosity do not significantly alter the Barrier Factor score nor the final WASP Index. For the purposes of travel time calculation, a range of typical n values are presented in Table 6. If accurate data are not available, a value of 20 % (or 0.2) is usually assumed.

The thickness of the barrier zone is defined by that zone between the base of the waste and the top of the aquifer. The top of the aquifer of unconfined and confined systems is relatively easy to define (Figure 12). Most aquifers in this country tend to range between these two end members. For all practical intents and purposes, the top of the aquifer is defined by the static piezometric surface. Depth to water can thus be used to define the thickness of the barrier zone. Modification to this protocol will only be allowed if detailed geological evidence is presented which shows that the rest water level does not define the aquifer's upper boundary.

Perched water table conditions were commonly claimed in the permit application documentation. A perched water table is a very specific and relatively uncommon geohydrological condition which implies no hydraulic continuity between two water-bearing formations. Should a perched water table be encountered, then the depth to the perched water table should be used. A decision to disregard the perched water table and use the regional water table will have to be strongly motivated, based on level 1 type data.

The range of thickness recorded in the permit application data is presented in Figure 13. It is evident that this data is usually measured during site investigations (Figure 14). It is not surprising to see that the most commonly recorded depth to water is within the 0 - 2.0 m range. Historically, it has been assumed in South Africa that a 2.0 m thick vadose zone was adequate.

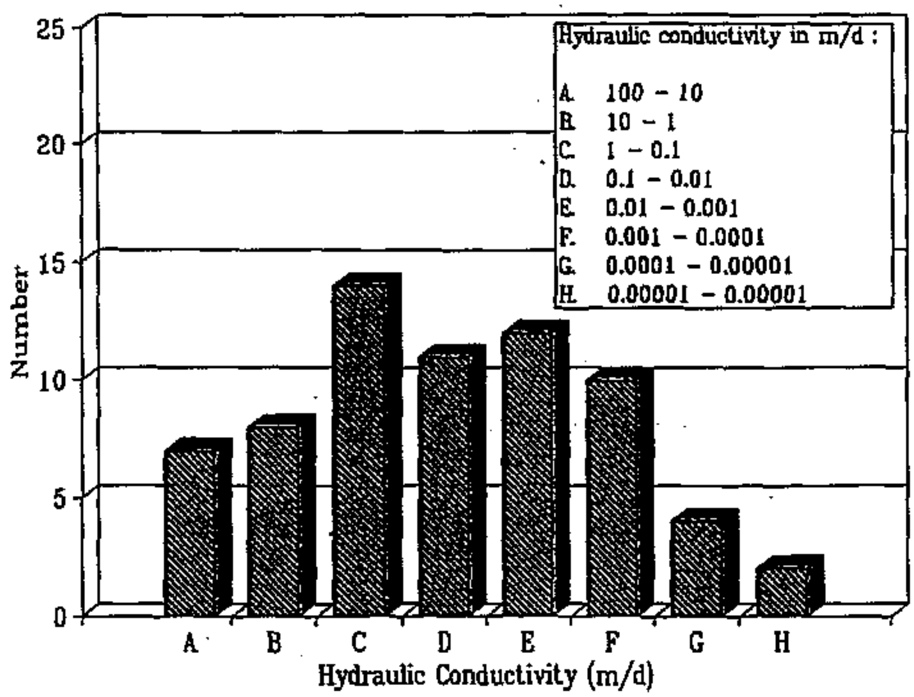


Figure 9: Range of K recorded at permitted waste sites.

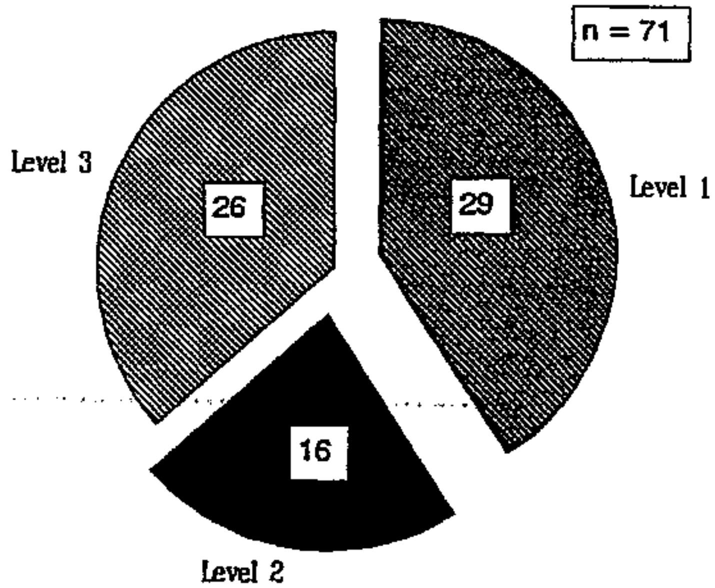


Figure 10: Reliability of K data.

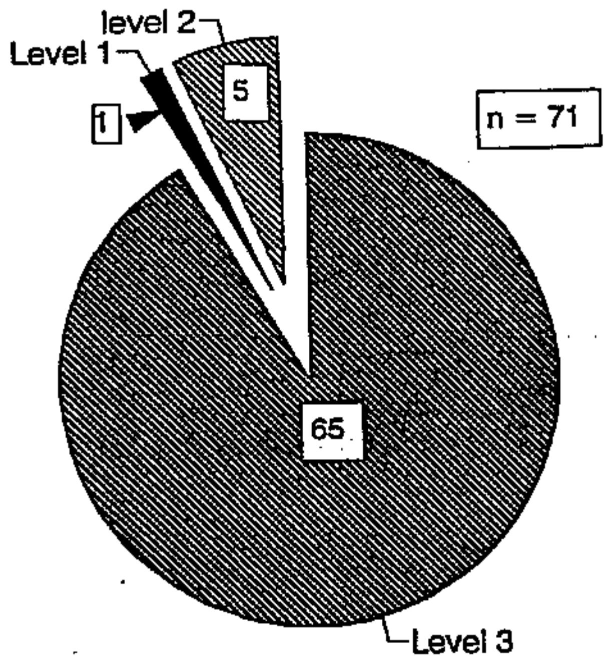


Figure 11: Reliability of porosity data.

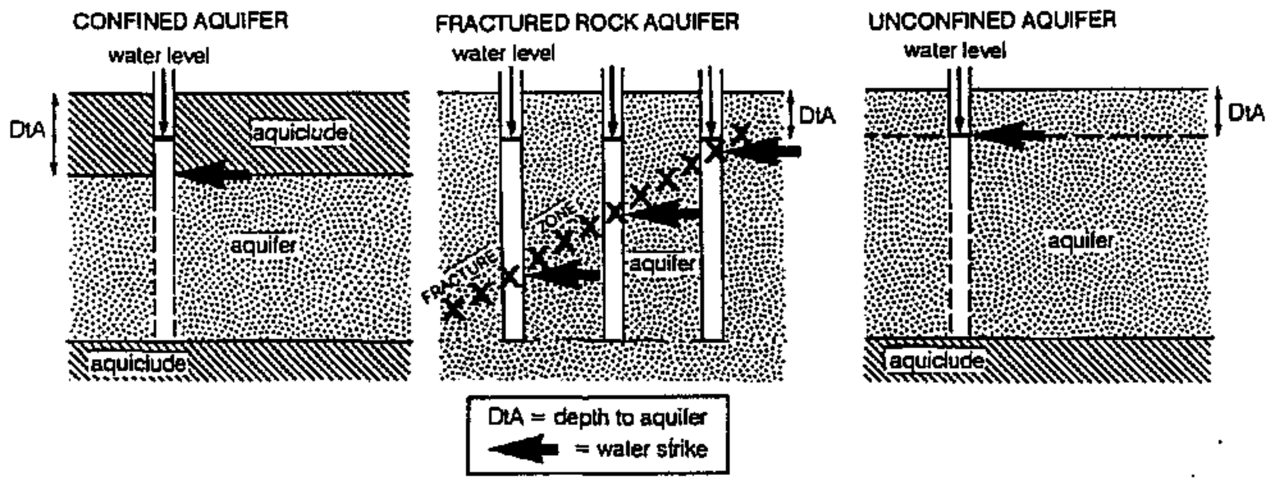


Figure 12: Aquifer types.

The data collected from the permit application documentation was used to estimate travel time (Figure 15). If this information is compared with the internationally applied standards (Table 8), then it is seen that South African practice applied in the past was well short of that required elsewhere. Further, the South African draft guidelines on waste disposal (NRPWM, 1986) required a barrier zone hydraulic conductivity of 8.64×10^{-4} m/d. If this requirement is coupled to the often applied 2 m unsaturated zone, then a travel time of only 462 days is estimated. This travel time period is very short when compared to international requirements (Table 8) and it is clear that requirements relating to the barrier zone need to be re-addressed.

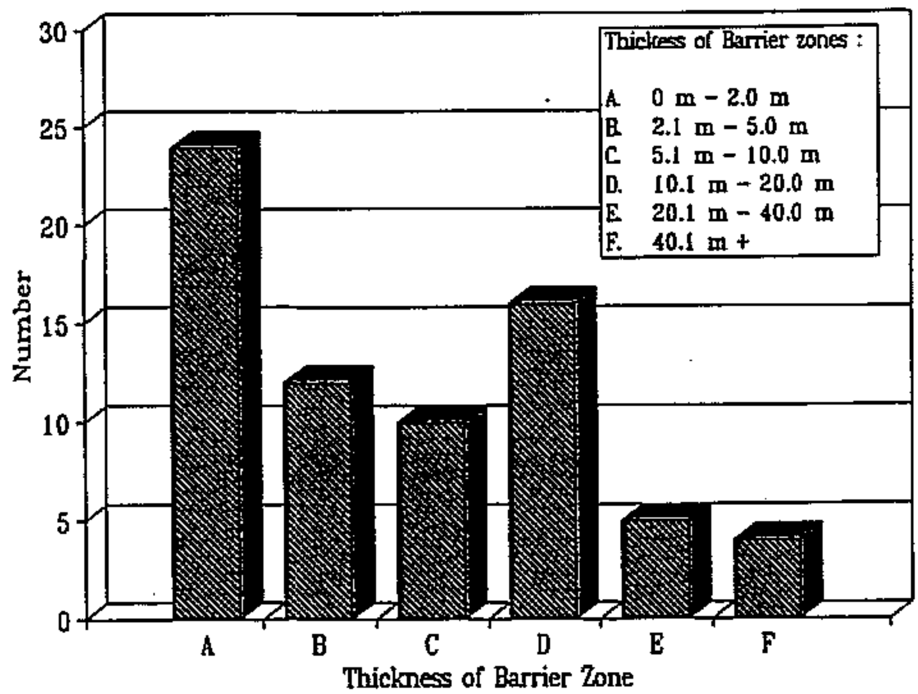


Figure 13: Range of depth to water data obtained from permit application documentation.

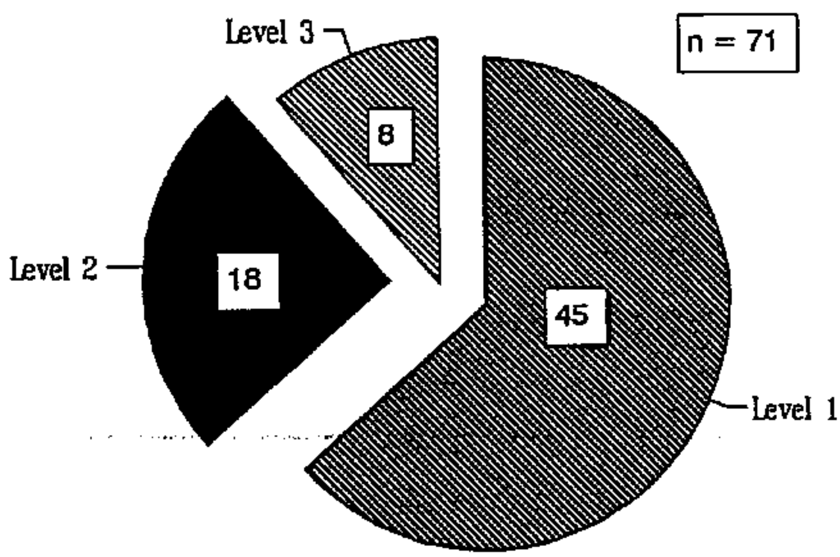


Figure 14: Reliability of depth to water data.

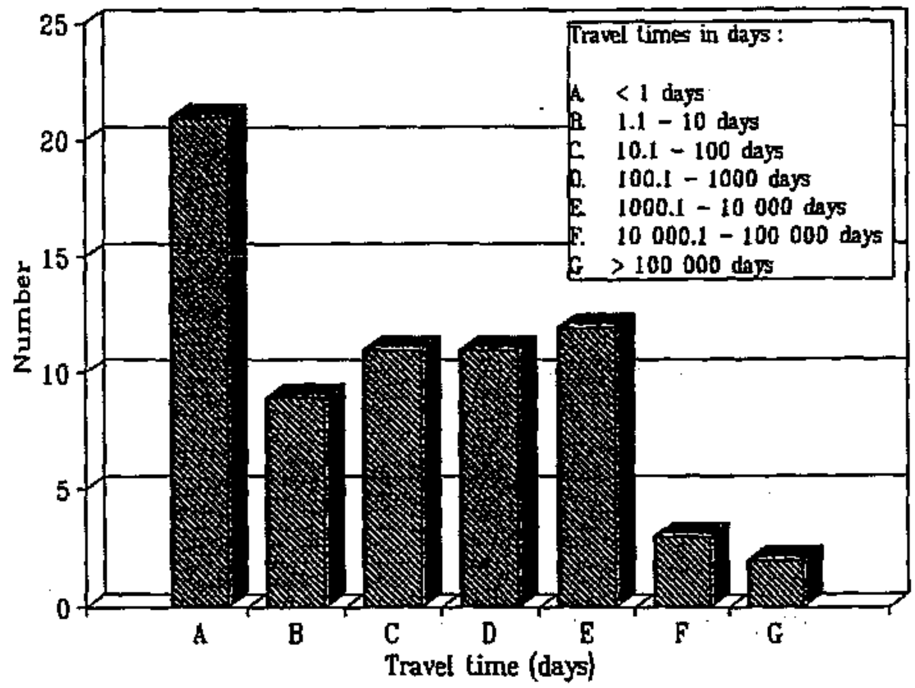


Figure 15: Range of estimated travel time, based on data collected from permit application documentation.

Table 8: International travel time requirements.

Country	Thickness (m)	K (m/day)	Travel time (days)	Reference
U.K.	-	-	36 500	Coleman, pers. comm., 1992
France	5	8.64×10^{-5}	11 315	Barres et al., 1989
Germany	5	8.64×10^{-4}	1 100 *	NLFB, 1991
US EPA	-		36 500	US EPA, 1989
European Council's Directive on the Landfilling of Wastes	3	8.64×10^{-5}	6 935	Eviron. Committee, 1991

* The travel time appears short, however, the site may not be developed over a potential aquifer, only an aquifer of "limited potential"

The calibration of the Barrier Factor nomogram (Figure 16) was based on the information presented above and on internationally accepted and practised standards. The calibration of the curve was thus based on:

a. a hundred year travel time (ie. 36 500 days) is the most stringent world requirement (EPA, 1989). A degree of conservatism was built into the nomogram to take into account preferential pathways and differential rates of movement of organic liquids. Furthermore, it was presumed that a totally impermeable barrier did not exist (Lee and Jones, 1991) so a score of 0 could never be realized. Ideal barriers were regarded to be those with travel times in excess of 36 000 days.
b. the German 1 100 day travel time (NLFB, 1991) was seen as being the marginal cut-off between acceptable and unacceptable. Any travel time less that 1 100 days would receive a score of above 5.0.
c. waste sites would not be emplaced above potential aquifers - if any potential aquifers occurred at some depth below a barrier, very strong motivation would have to be provided regarding the adequacy of the barrier.

The subjective curvature of the line in Figure 16 has been used to comply with the precautionary approach adopted in this study. If the line were straight, for example, this would imply that at some point, the barrier would be totally effective in separating the waste pile from the groundwater body. In light of present knowledge on leachate attenuation and the difficulty in measuring parameters in the geological environment, it would be dangerous to promote the concept of such an effective barrier.

The calculation of the Barrier Factor score is relatively simple. Once the travel time has been determined, Figure 16 is used to relate travel time to the Barrier Factor score.

The definitions used in the assessment of the reliability of the data used to quantify the Barrier Factor score are presented in Table 9. Each component is rated individually and an average obtained. The data reliability rating is recorded and later used to define the overall data reliability rating.

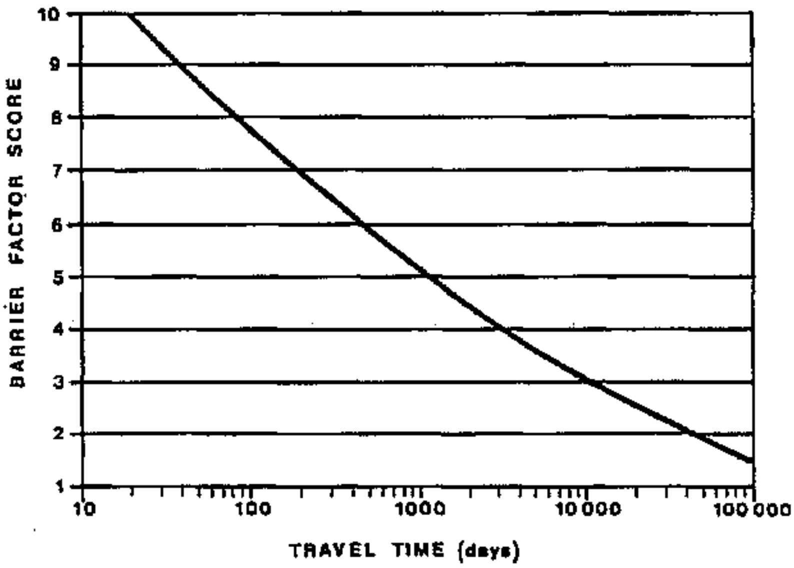


Figure 16: Barrier Factor score nomogram.

Table 9: Scales for rating data reliability for the Barrier Factor

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Thickness	Certain - based on site specific measured depth to water, drilling data and geohydrological borehole log	Based on measure depth to water, extrapolated information from similar areas	Uncertain - based on estimation from national or regional maps, guesstimation
K	Certain - based on site specific *in situ* tests - aquifer tests, borehole percolation tests, double ring infiltrometer tests etc.	Based on laboratory analyses, surface infiltrometer tests, extrapolated information from similar lithologies, standard tables.	Uncertain - based on standard tables, guesstimation
Porosity	Certain - based on field analyses and laboratory analyses	Based on extrapolation from similar lithologies, standard tables	Uncertain - based on standard tables, guesstimation

6.4. Resource Factor

The questionnaire used to quantify the Resource Factor was developed around the discussion presented in Section 5.4. It was initially decided that three aspects would be covered, namely:

a. groundwater usage
b. groundwater potential
c. alternative water sources

The first two components were aimed at directly satisfying the information needs presented in Section 5.4. (Table 10). The latter component was included in order to provide perspective on the strategic value of groundwater, to help balance some of the economic realities of waste disposal if contamination were to occur and to provide an indication of the feasibility of using other water sources *in relation* to groundwater resources. It was, however, found that 82 % of the cases studied had feasible alternative water sources (Figure 17) while only 4 % of the cases had no alternative water sources. It was also found that little reliable data were readily available (Figure 18) and answers to the questions posed were largely obtained from either DWAF (1986) or were based on the researchers' own personal knowledge. Factor scores compiled using the points from all three components were correlated against a similar factor score based only on the groundwater usage and groundwater potential components (Figure 19). It was clearly evident that the alternative water sources component had little impact on the outcome of the factor score. It was hence decided that the alternative water sources component would be excluded from WASP.

Table 10: Questions used in the quantification of the Resource Factor

Groundwater Usage	Groundwater Potential	Alternative Water Sources
a. Is groundwater used to meet present water requirements in the area immediately adjacent to the site? b. Is groundwater used within 2 km of the waste pile? c. Is the waste pile located up-gradient of the groundwater users? d. What percentage of water demand is met from groundwater resources?	a. Does the geology of the area portray any features typically associated with usable aquifers? b. Is the long-term safe yield of the aquifer sufficient to fully or partially meet local demand? c. Can the aquifer be used for drought relief purposes or be used locally for reticulation management? d. Is the groundwater quality such that it is fit for use by the potential user? e. Is the waste site the only contamination risk which could threaten aquifer potential?	a. Excluding groundwater, do other conventional or non-conventional alternative water sources exist? b. Are these other alternative water sources capable of meeting demand over the next 30 years? c. Is the development of these alternative water sources affordable by the community to be served? d. Is the risk of resource degradation by contamination to these alternative water resources low? e. Is it true that no other water users are or could compete for these alternative water resources?

It should be noted that the 2 km standard set in Table 10 is merely a guide. Should it be warranted, for example, in the case of sites larger than 50 ha or for sites which accept hazardous waste, this distance may be increased.

The sentence structure of each question in Table 10 was carefully prepared so that an answer with a particular bias was obtained ie. a *yes* answer would indicate an aquifer of strategic value. This allowed that 2 points could be assigned to each *yes* answer and hence calculate a quantified value for the Resource Factor. In line with the precautionary principle (Section 5.4.2.), 2 points were also assigned to *do not know* or *maybe* answers. A bar scale was developed to assign points with respect to the percentage of groundwater used (Figure 20). The component scores could then be determined by answering the two sets of questions. For each question 2 points are assigned for each *yes* answer and points are also awarded based on the percentage of groundwater used. All points are then added to yield a total for each component.

The groundwater usage data showed that the questions were able to identify clearly those instances were groundwater was being used (Figure 21), as well as give an indication of the relative value of the resource. The reliability of the data obtained from the permit application documentation and available geohydrological reports was relatively good (Figure 22). The groundwater potential component showed a good spread of values across the possible range (Figure 23), while data reliability was similar to that of the groundwater usage component (Figure 24).

On investigating the most appropriate means of obtaining an effective Resource Factor score, the use of only the groundwater potential component was considered. It was, however, found that in certain cases, the groundwater usage score exceeded the groundwater potential score (Figure 25). This pointed to some aquifers being used even though they showed few characteristics typically associated with aquifers of good groundwater potential. The converse was also found to be true, but this was expected as many aquifers are not used to their full potential.

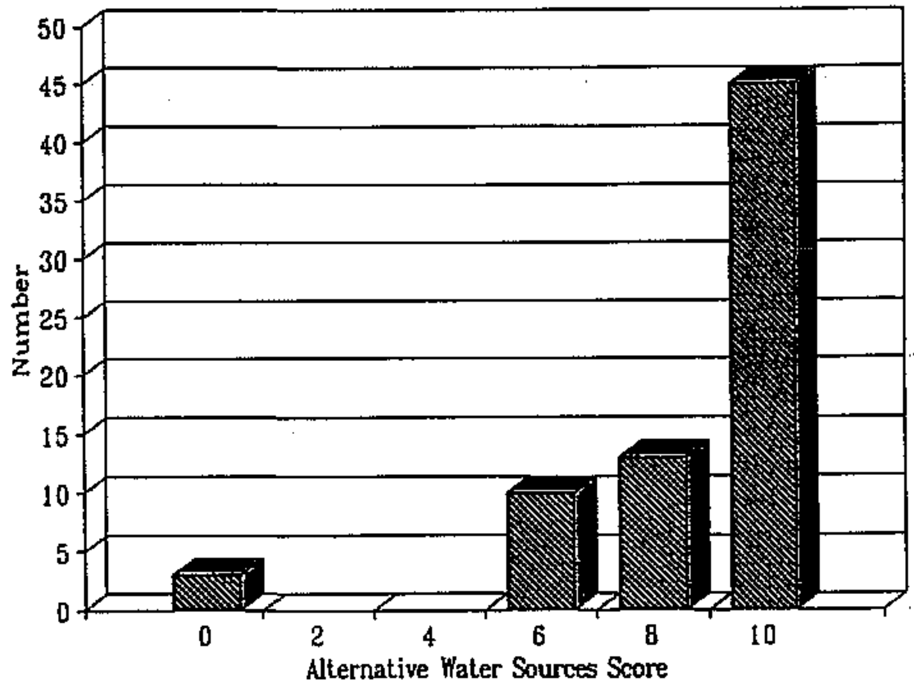


Figure 17: Range of alternative water sources scores, with 10 indicating the existence of alternative water sources and 0 indicating that no feasible alternative water sources exist.

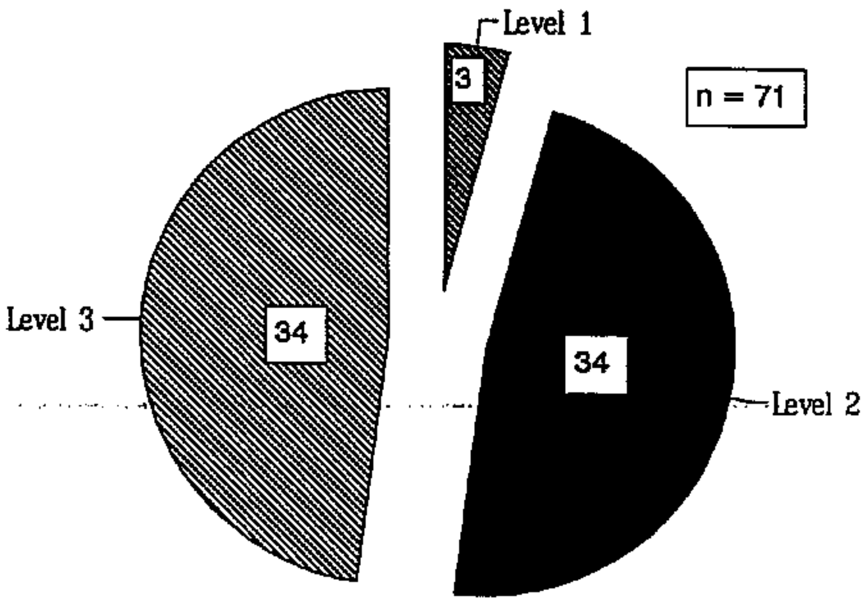


Figure 18: Reliability of alternative water sources data

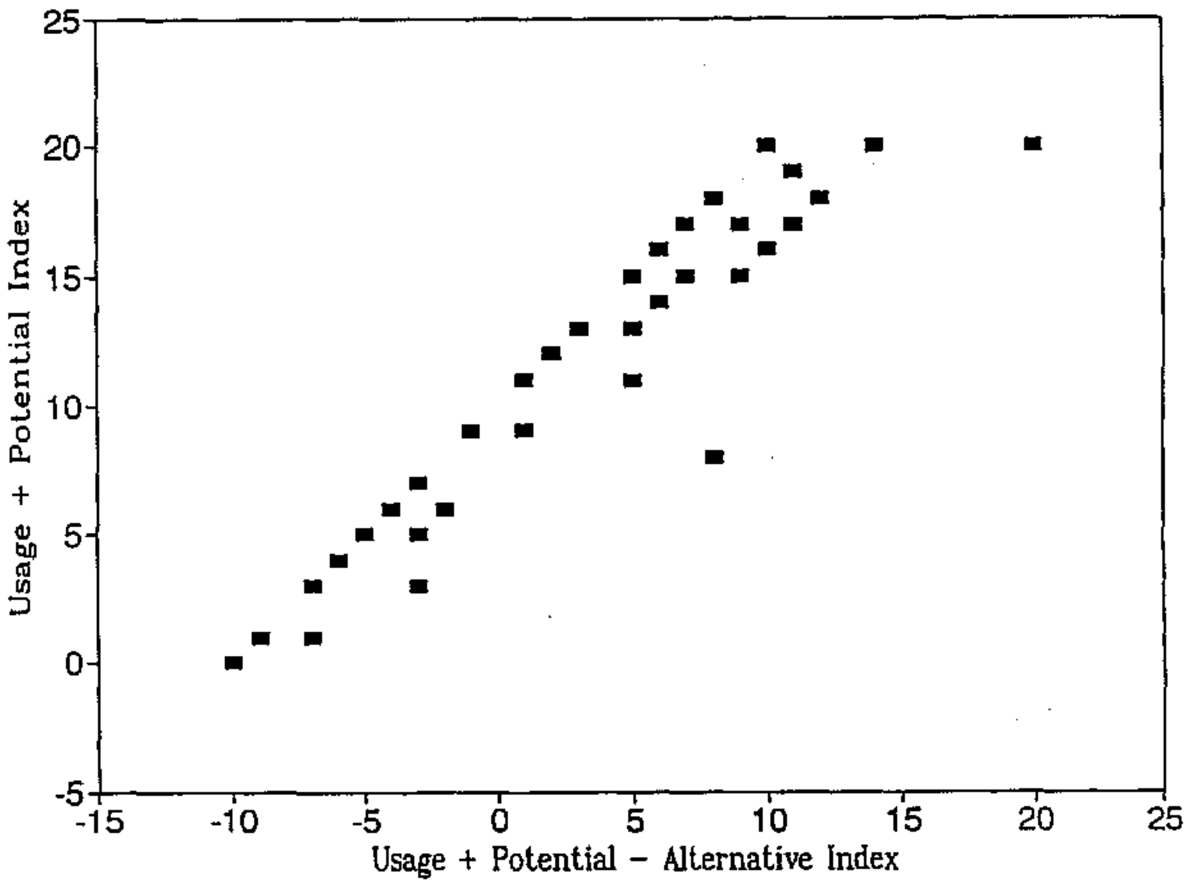


Figure 19: Correlation between a factor score derived from all resource components and a factor score based only on the groundwater usage and groundwater potential components.

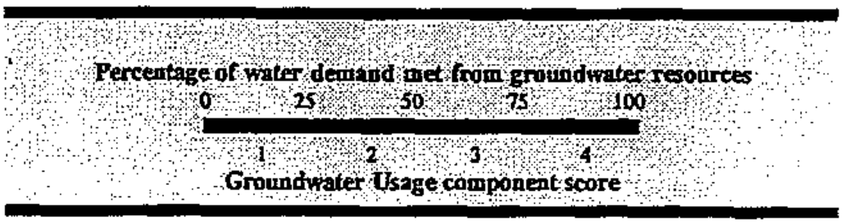


Figure 20: Bar scale used to assign points for the percentage of groundwater used to meet water demand.

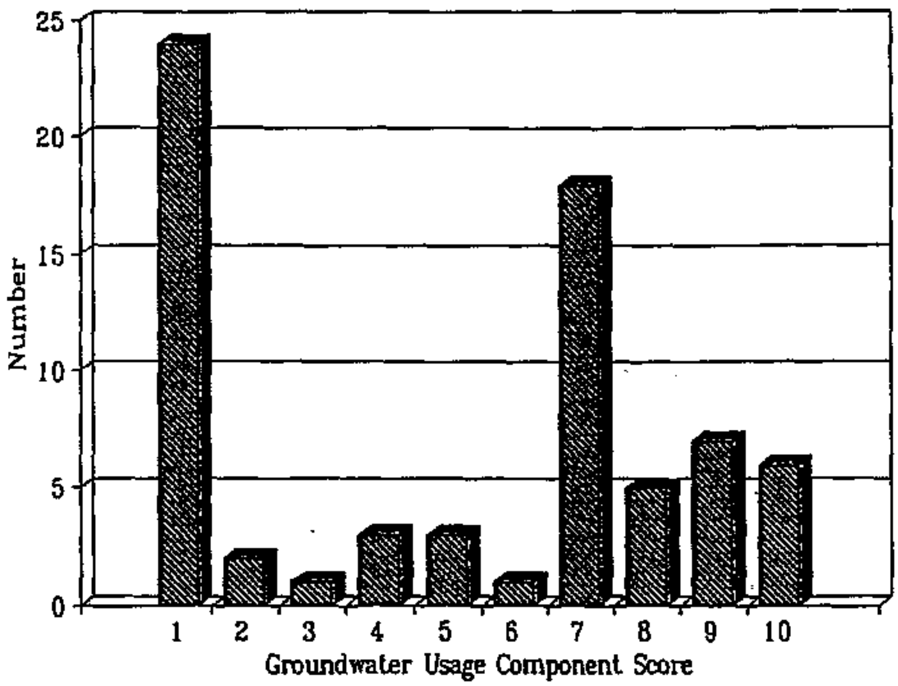


Figure 21: Spread of scores obtained for the groundwater usage component

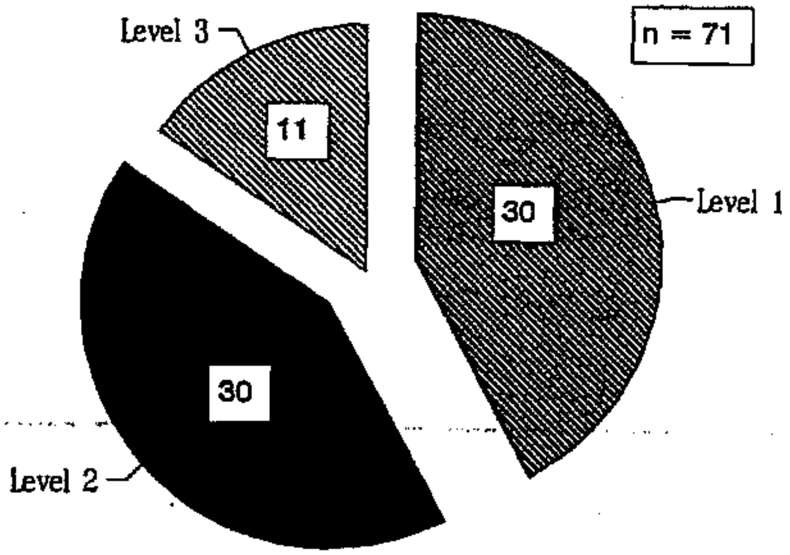


Figure 22: Reliability of groundwater usage data

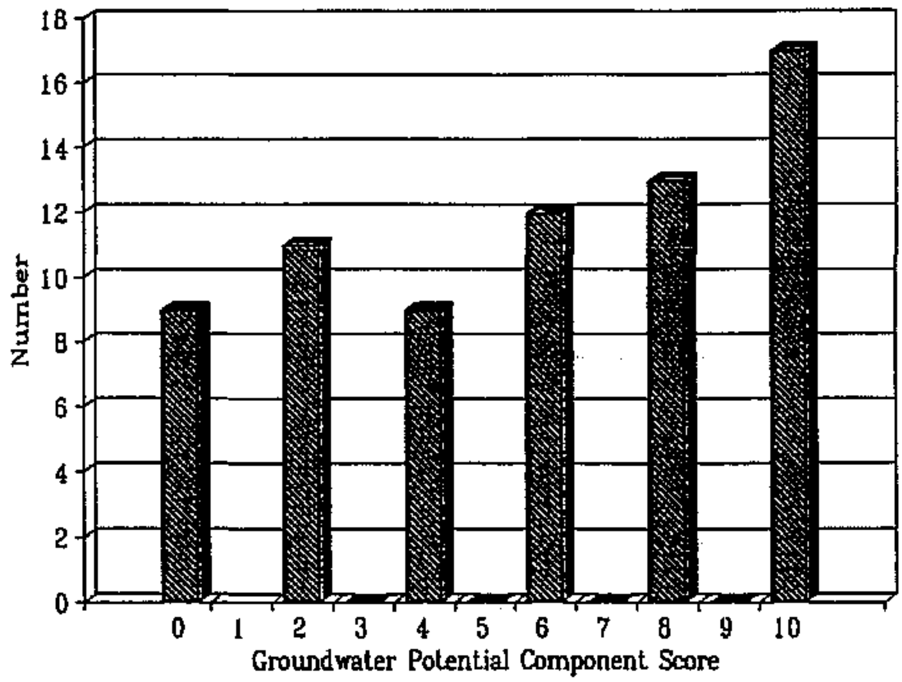


Figure 23: Spread of scores obtained for the groundwater potential component

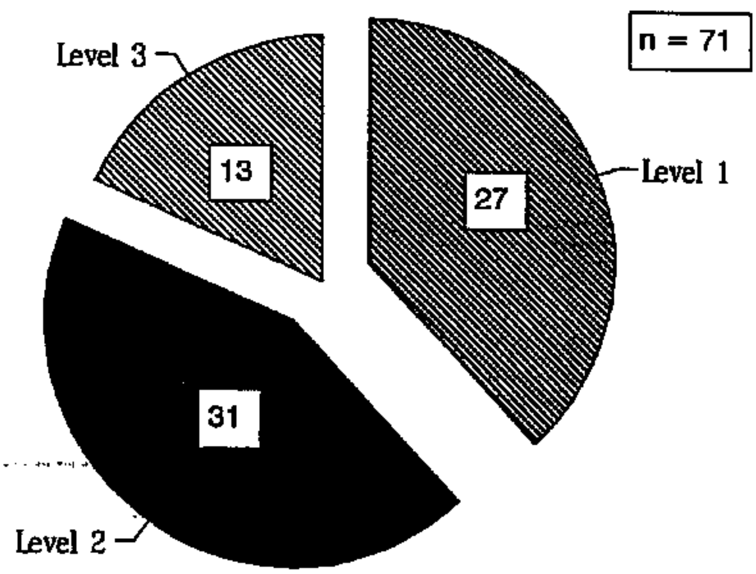


Figure 24: Reliability of groundwater potential data

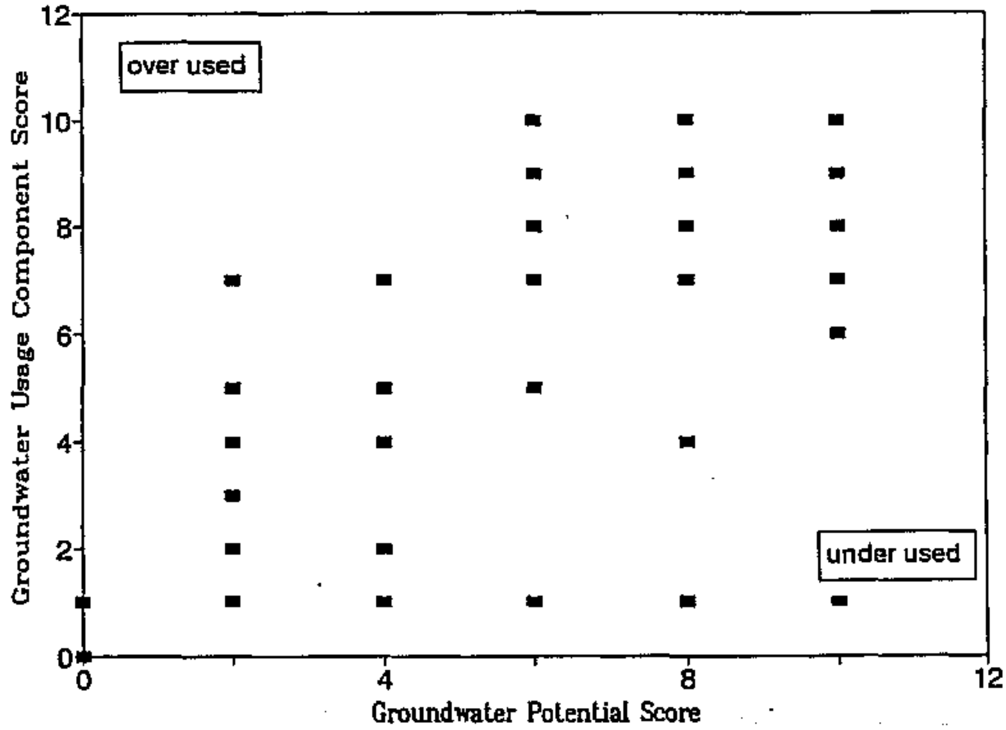


Figure 25: Correlation between Groundwater Usage and Groundwater Potential component scores.

It was found that adding the two component scores had some positive attributes:

a. differentiation was possible between good aquifers being used, potential aquifers not being used and groundwater bodies with low potential.
b. in cases where usage exceeded potential, a higher strategic value was recognised - this, in fact, partially replaced the need for the alternative water sources component which had been rejected earlier.

The relationship between the added Groundwater Usage and Groundwater Potential component score and the strategic value was not regarded to be linear. The low scores equated to much less of a strategic value than the higher scores. The precautionary principle also required some conservatism in setting the Resource Factor score. The non-linear relationship set out in Figure 26 was accordingly adopted.

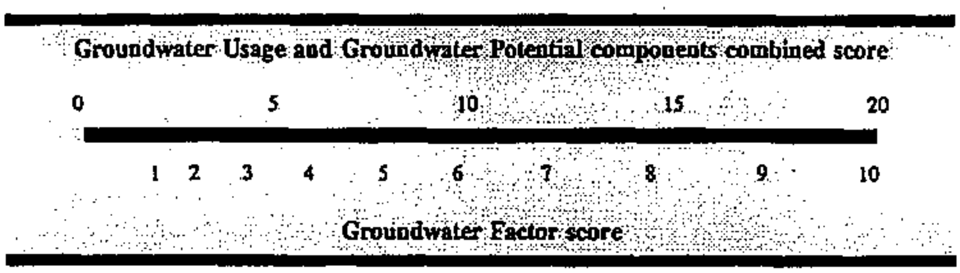


Figure 26: Bar scale used to obtain Resource Factor score from combined groundwater usage and groundwater potential component scores.

The data reliability of the Resource Factor is calculated using the rating scales presented in Table 11. The individual components are rated and an average for the Factor is obtained. The data reliability rating is then used to determine the final WASP Index data reliability rating.

Table 11 : Scales for rating the data reliability of the Resource Factor

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Groundwater usage	certain - based on full hydrocensus, records and reports.	based on partial hydrocensus and discussions with local residents, driller or geohydrologist.	uncertain - based on estimations.
Groundwater potential	certain - based on full geohydrological investigation and detailed study.	based on extrapolation of information from other areas, discussions with local geohydrologists familiar with the area etc.	uncertain - based on estimations, interpretation of regional and national geological and geohydrological maps.

6.5. WASP Index Determination

There was no manner in which to firmly establish the numeric relationship between the Threat Factor, the Barrier Factor and the Resource Factor in terms of assessing the suitability of a site for waste disposal. During the evaluation of the permit application data, it was apparent that the WASP method provided a logical, easy and rapid qualitative means of assessment. It provided a means of organising ones thoughts in considering each situation in a holistic fashion. Sites with a low Threat Factor score, a low Barrier Factor score and a low Resource Factor score were clearly acceptable and conversely, sites with a high Threat Factor score, a high Barrier Factor score and a high Resource Factor score were clearly unacceptable. The intermediate range of values were, however, more difficult to appraise. Specific knowledge of the site under consideration and the professional judgement of the researchers had to be used.

It was decided that a linear relationship between the three Factors would be assumed until such time that sufficient field information were available from which a more accurate relationship could be ratified. It was felt that such an approach to the problem was not unreasonable since a conservative pattern had been followed in quantifying the three Factors. Further, the verification of the relationships using the field data from the 10 sites studied in detail would provide some evidence of the validity of adopted linear relationships.

Even though the linear relationships could be easily calculated by adding the three Factor scores and obtaining an average, it was decided that the WASP Index would be determined more effectively using a nomographic solution. This decision was based on:

a. the technique providing a clear visual representation of the magnitude of the individual Factors and their inter-relationship, and
b. the mathematical relationships between the different Factors, if and when properly established, could be easily incorporated into the nomogram without requiring any major change to the technique or procedure.

The WASP Index nomogram is presented in Figure 27. As a means of gaining some insight into the value of the Index, qualitative suitability ratings were given to 41 of the 71 sites from which data was used in the quantification of WASP. Ratings of 1 to 5 (suitable to unsuitable) were assigned to each site by the researchers, based on their knowledge and assessment of the site and on opinions expressed by the people visited in execution of the research project. Exclusion from this exercise was based on the researcher's lack of knowledge of the site. It was found that a close correlation was obtained (Figure 28). Initial investigation into the poor correlations revealed 3 data typing errors and 2 poor subjective assessments. After corrections were made, the following considerations accounted for the discrepancies:

a. cases 1 and 2, marked on Figure 28, are large sites which accept hazardous waste and, even though geohydrological conditions are poor, groundwater is used for farm domestic water supply and stock watering. At both sites it needs to be properly established whether the aquifer being used is in hydraulic continuity with the groundwater bodies beneath the waste sites.
b. with regard to case 3, the geohydrological potential is high, but it is highly unlikely that groundwater will be used owing to proximity to the Orange River.
c. cases 4 and 5 are major sites which have been engineered (bottom liner, leachate collection systems), however, both are located on major geological structural features.
d. even though case 6 is a small site which will probably not have a significant impact on the aquifer, it is located in fairly close proximity to a major primary aquifer.
e. a higher subjective rating of both cases 7 and 8 may have been warranted.
f. cases 9 and 10 are small sites which have had a measurable impact on the used groundwater resources - it might be that the small size of the sites resulted in a slightly lower WASP Index than should actually be the case.
g. case 11 is a major waste facility located on a primary aquifer, however, the real value of the aquifer has not been fully tested. Its close proximity to the sea and the existence of other sources of contamination may, in fact, result in a lower strategic value. Until such time that the true value of the aquifer is established, a conservative approach will be applied.

Note that cases 1 to 11 presented above relate to those discussed in Figure 28 and not to Sites 1 to 10 used in the validation of the WASP method. From the evaluation of Figure 28 it was possible to provide a generalised interpretation of the WASP Index (Table 12). This interpretation was to be tested using the information and knowledge concerning the sites studied in detail (Section 7.1).

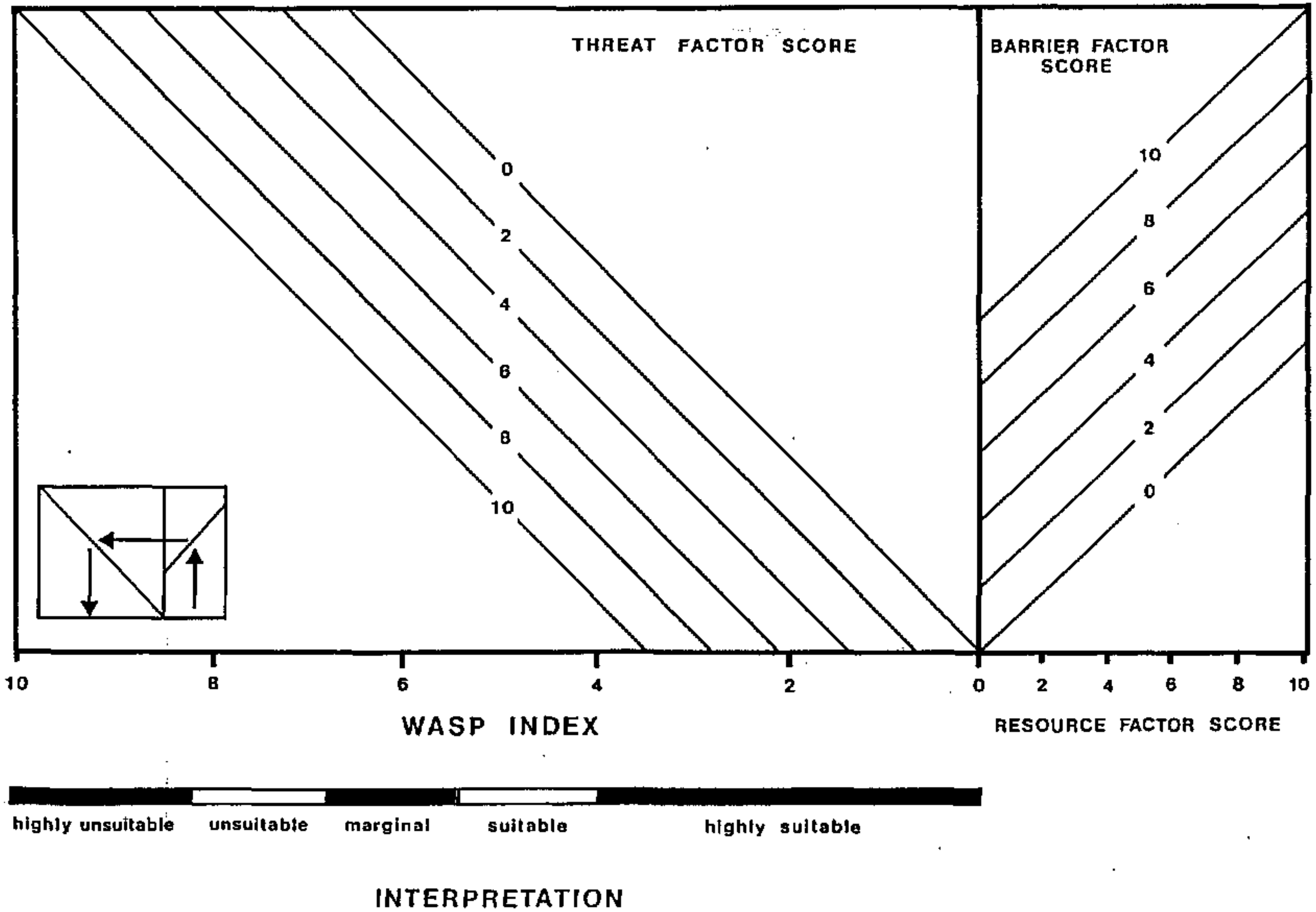


Figure 27: WASP Index nomogram

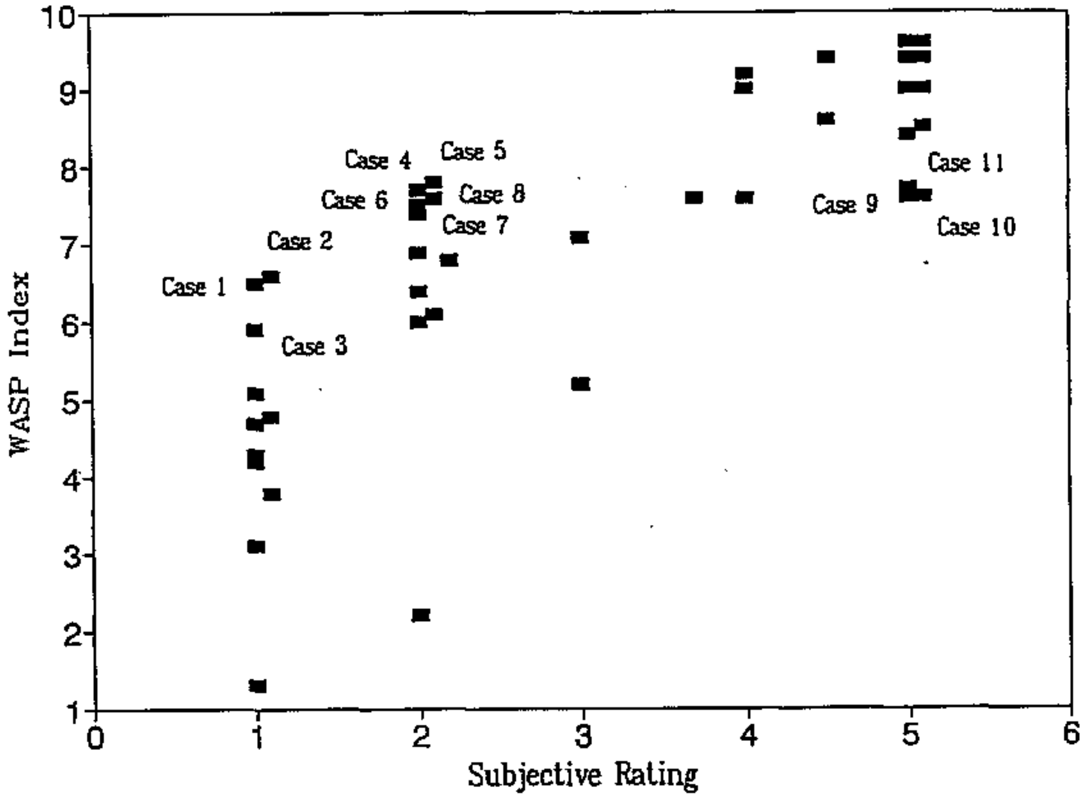


Figure 28: Correlation of WASP indices of selected sites and subjective assessments of the same sites.

Table 12: Site suitability related to WASP Index

Site Suitability	WASP Index
highly suitable for waste disposal site	< 4.0
suitable for waste disposal site	4.0 - 5.4
marginal	5.4 - 6.8
unsuitable for waste disposal site	6.8 - 8.2
highly unsuitable for waste disposal site	> 8.2

The data reliability level (Section 5.5.) should be written behind the WASP index, in parenthesis. This allows that the degree of detail and confidence in the assessment can be recorded. As this is a simple averaging procedure, a low figure (less than 2.0) indicates that essentially detailed and measured data was used while a high figure (greater than 2.0) suggests that much of the assessment was based on estimation and extrapolated data.

7. WASP VALIDATION

7.1. Assessment of Obtained WASP Indices

All relevant data concerning the 10 sites studied in detail during this study are presented in Table 13. The individual factor scores and the WASP Index are also presented, but only the final data reliability index is presented. Brief assessment of the WASP Index obtained for each site are presented below.

Site 1

The obtained WASP Index of 8.2 for the site is regarded to be accurate. Significant contamination has been detected. Even though the waste site is located some distance from the wellfield and probably poses little threat to the resource, it is not good practice to place any waste facility on an aquifer or parts of an aquifer. A number of lithologies are found nearby which would be better suited for waste disposal activities.

Site 2

The WASP Index of this site (4.8) is regarded to be representative of the site. The very poor quality ground water suggests that the groundwater in the area has no strategic value, nor is it likely to have any value in the future. The groundwater quality plays such a significant role in the evaluation of the site that it could be considered to be an *over-riding* factor. The threat posed by the waste pile is relatively small while the barrier will promote some attenuation.

Site 3

An Index of 4.2 is regarded to be representative of the site. Even though the waste pile poses a significant threat, the extremely thick, low conductivity barrier zone and the poor quality groundwater indicate that very little risk is posed to groundwater bodies and that the groundwater of the area has no, nor will have, any strategic value. The barrier factor and groundwater quality can be considered to be *over-riding* factors.

Site 4

The high rating obtained for Site 4 (9.7) is regarded to be realistic. The threat posed by the now buried waste pile and the strategic value of the dolomitic aquifers are well established. The debate concerning the suitability of the site for disposal revolves around the ability of the Karoo outlier to keep the waste and aquifer separated. The fractured nature of the material indicates that preferential flow will occur.

Table 13: WASP data for sites investigated in detail during research project.

FACTOR	SITE 1	SITE 2	SITE 3	SITE 4	SITE 5
Threat Factor					
- designed final area (ha)	6	16	15	7	4
- waste type	dom. and comm.	domestic	toxic	indust. effluent	dom. and sewage
Score	4.6	5.4	10.0	9.1	8.2
Barrier Factor					
- depth to water (m)	1.77	1.60	5.00	11.00	3.00
- K (m/d)	35	0.003	0.000008	0.8	18
- n (%)	30	20	20	20	20
- travel time (days)	0.02	107	125 000	2.8	0.03
Score	10.0	7.6	1.5	10.0	10
Resource Factor					
- groundwater usage	10	1	1	10	10
- groundwater potential	10	0	0	10	8
- combined total	20	1	1	20	18
Score	10.0	0.5	0.5	10.0	9.3
WASP Index	8.2 (1.2)	4.8 (1.2)	4.2 (1.2)	9.7 (1.3)	9.1 (1.2)

Table 13 (cont.): WASP data for sites investigated in detail during research project.

FACTOR	SITE 6	SITE 7	SITE 8	SITE 9	SITE 10
Threat Factor					
- designed final area (ha)	1	1.5	15	30	25
- waste type	domestic	domestic	liquid effluent	indust. effluent	dry industrial
Score	3.2	3.5	10.0	10.0	8.3
Barrier Factor					
- depth to water (m)	6.36	12.14	2.00	4.40	2.59
- K (m/d)	1.3	0.015	0.01	0.08	21
- n (%)	20	20	20	20	20
- travel time (days)	0.98	162	40	11	0.02
Score	10.0	7.1	8.9	10.0	10
Resource Factor					
- groundwater usage	10	7	1	1	10
- groundwater potential	10	8	4	0	8
- combined total	20	15	5	1	18
Score	10.0	8.2	3.4	0.5	9.3
WASP Index	7.7 (1.2)	6.3 (1.2)	7.5 (1.2)	7.0 (1.7)	9.2 (1.2)

This, coupled to a shallow depth to water, indicates that the separation barrier is ineffective. The fact that contamination has already been detected supports the high WASP Index.

Site 5

The high WASP Index of 9.1 is accurate in this case. The waste site is located on a used aquifer which has a very high strategic value to the town which it serves. The production wellfield is located 700 m away from the site. The barrier has no attenuating capabilities and the threat posed by the waste disposal activities is high, principally due to the co-disposal of sewage. Contamination down-gradient of the site has been detected.

Site 6

A WASP Index of 7.7 is regarded to be slightly low for this site, but it still indicates an unacceptable situation. The waste site is located over a dolerite dyke. The high yield of production boreholes located directly adjacent to the site is a direct result of the dyke. The barrier has no attenuating capabilities and contamination has been detected. The level of contamination is, at this stage, relatively low considering that the site is almost 20 years old. However, true contamination levels may be masked by continual recharge of good quality water from a dam located on the dyke, up-gradient of the waste site. The slightly low Index is a direct result of the relatively small risk posed by the waste pile.

Site 7

The marginal interpretation of Site 7 (6.3) is regarded as accurate. The threat posed by the waste pile is small, but the barrier has been effectively removed through quarrying. Groundwater is used in the area, but its strategic value is probably not as high as the Resource Factor would indicate. Some degree of site engineering would be required if the site were to meet modern sanitary landfill standards.

Site 8

The WASP Index of 7.5 obtained for this site is regarded as being accurate. The waste poses a significant threat while an ineffective separating barrier exists. Little groundwater is used in the area, but the geology portrays features which suggest that an aquifer of strategic value exists. Localised contamination was detected directly down-gradient of the waste pile.

Groundwater could be used on a small scale by the local community. The site is bordered by a cemetery and a major third world township, both of which lower the strategic value of the resource. The presence of these two potential pollution sources was not considered to constitute an over-ride factor. Strong motivation does, however, exist to accept the site as being suitable based on factors outside of WASP, namely:

a. sufficient feasible alternative water resources,
b. better geohydrological potential existing elsewhere in the greater region around the city,
c. limited available waste facilities near the industrial area.
d. engineering and appropriate management of the waste facility.

Site 9

The WASP Index of 7.0 accurately reflects the geohydrological assessment of this site. The waste pile poses a significant threat while a relatively ineffective barrier zone exists. The groundwater resources of the area around the site, however, have limited strategic value and no contamination was detected. It is proposed that continual recharge from the river could nevertheless mask any contamination. The low Resource Factor score could constitute an *over-ride* factor.

The impact that the site has on surface water resources, and the role that subsurface flow has in this regard, needs attention. The marginal interpretation is hence appraised as being appropriate.

Site 10

The perceived strategic value to the city of the primary aquifer adjacent to the waste facility, particularly during periods of drought, indicates that the a WASP Index of 9.2 is justified. The threat posed by the waste pile is high while the vadose zone has very little attenuating capabilities. The fact that contamination could not be confirmed is not regarded as a limitation in the evaluation of the obtained Index. Theoretical calculations of possible lag times before contamination would be detected, show that it may be another 2 to 3 years before detection at the available monitoring stations will occur.

7.2. Discussion of Validation Results

7.2.1. General performance

All of the obtained WASP Indices were found to provide accurate quantitative assessments of the geohydrological conditions prevailing at the sites considered in more detail. The Index obtained for Site 6 was regarded to be slightly low. This resulted from the small threat posed by the waste pile. The WASP Index obtained was nonetheless still valid in terms of the acceptability of the site.

If the performance of WASP in evaluating the permit application data is also considered (Section 6.5.), then the ability of WASP to provide qualitative assessments must be recognised. Even though every effort was made to base the development, calibration and verification on as much data as possible, more good quality and reliable data will be required to confirm the calibration presented here. At the moment this data is not available. As the waste site permitting drive of DWAF continues, the required data will be obtained.

7.2.2. Over-ride factors

It is accepted that WASP cannot be applicable to all situations. It was found that, at times, some factors were of such importance that they over-ride the other factors. Accommodation of these *over-ride* factors must be allowed for in the procedure. An over-ride factor is thus defined as a factor of such importance that it, in itself, can be used to determine the suitability of a site for waste disposal. Over-rides may be either single items, components or factors. The following examples are used to illustrate the concept:

a. the extremely poor groundwater quality recorded at Site 2 results in the groundwater resources having no strategic value, irrespective of the hydraulic capabilities of the system - it was found that groundwater quality was a fairly common over-riding consideration.
b. The Sundays River Formation is known to be an aquiclude with no geohydrological potential in terms of both quality and quantity - the extreme thickness of this Formation at Site 3 is an over-ride, as is the poor quality and long travel time.
c. the proximity of both Site 5 and Site 6 to groundwater supply abstraction schemes could be constituted as over-rides - WASP is however capable of coping with such situations.
d. the extremely low Groundwater Factor score of Site 9 could also be regarded as an over-ride - no resource exists which needs protection, irrespective of the high Threat Factor and absent barrier zone.

It is not possible to provide guidelines on when a particular consideration becomes an over-ride. The *professional judgement* of the *geohydrologist performing the assessment* must be relied on to identify such factors and to motivate why they should in fact be afforded over-ride status. However, such motivation may only be based on data with a level 1 data reliability rating ie. measured and quantifiable field data, which is sufficient to conclusively prove that the over-ride is valid.

7.2.3. Need for more detailed specific investigation

It was found on at least three occasions during this study, that two different groundwater bodies existed within the area of consideration around the waste site. The waste sites were in fact located on aquitards or aquicludes which were acceptable for waste disposal ie. good barriers and no resource. However, within the 2 km study area surrounding the site, groundwater was abstracted from a different water-bearing lithology than that underlying the site. In the strict application of WASP, both the usage and potential of the distant geohydrological unit had to be considered.

The application of WASP does, however, require some degree of flexibility. In these particular instances, a geohydrological study could be carried out to establish whether the different geologic units are in fact in hydraulic continuity. If they are found to be in continuity, the initial WASP Index would stand. If it could be clearly shown that hydraulic continuity did not exist, then a re-assessment of the situation could be performed whereby the usage and potential of the water-bearing geology could be excluded. Such assessment into special or specific geohydrological circumstances would have to be performed by an appropriately qualified and experienced geohydrologist, while the data used to prove the validity of these special conditions would have to be of a level 1 data reliability rating.

7.3. Need for Further Verification and Validation

Throughout this research project, emphasis has been placed on the validation, verification, calibration and accuracy of the method to be developed. Recent debate in the literature has presented differing perspectives regarding this topic (Bredenhoeft and Konikow, 1993; McCombie and McKinley, 1993). Like the word *aquifer*, these terms all have a number of shades of meaning. It must also be remembered that geohydrology is not an exact science and definitive answers to complex situations are difficult and often costly to provide.

The development of the WASP method was based on 30 different methods applied throughout the world. In the development, however, local conditions such as the predominance of hard rock fractured aquifers and the high value of water in a semi-arid environment were important. The method was checked for correctness (verified) by evaluating the performance of the WASP Index against subjective site ratings. All available reliable permit application data was used in this process. The method was then validated and calibrated by comparing the WASP Index against observed geohydrological behaviour at 10 well studied sites. Based on the results obtained during verification and validation, it is apparent that WASP is capable of accurately reflecting the suitability of a site for waste disposal activities, in both a qualitative and quantitative manner, based on geohydrological considerations.

The question which has to be posed is whether the work performed is sufficient to provide enough confirmation that the method does in fact model the geohydrological conditions accurately and that the answers provided will be dependable. If Kok's (1992) and CSIR's (1991) respective estimates of 1 200 and 1 400 waste disposal sites existing in South Africa are accepted, then almost 10 % of these have been studied to one degree or another during this research project. These 10 % are regarded to be the sites with the most reliable data currently available. Additional verification and validation is required so that the accuracy of the model can be checked in even more detail.

Until such time that this additional data are available and based on the good performance of WASP in quantitatively assessing the suitability of waste disposal facilities on geohydrological criteria, it is recommended that:

a. the use of WASP be promoted so that it's performance in a greater number of situations can be assessed,
b. its use in the DWAF permit application process be implemented, and
c. a follow-up study be commissioned in 2 to 3 years time in order to evaluate all additional permit application information that becomes available and to re-evaluate the performance of WASP.

8. DISCUSSION

8.1. Application of WASP

WASP was developed as a tool for assessing the suitability of both existing and proposed sites for waste disposal, based on geohydrological criteria. In contrast to the well-known DRASTIC method, it is suitable for site specific investigations.

There is a need in South Africa for uniformity and standardisation in the evaluation of waste disposal sites. WASP provides the tool for central Government permitting authorities, local authorities, private waste companies and consultants to evaluate sites on a comparable basis. All individuals and organisations will be able to gain some understanding of the factors that need to be considered, the data required to perform the assessment and the reasoning of why a site is regarded as suitable or unsuitable. The only real debate between the owners of a site and the permitting authority would thus centre on the detail and reliability of data required before a final decision concerning the suitability of a site can be taken. Some detailed technical considerations may also be required, but this would usually be the responsibility of the professional doing the assessment. For WASP to be used correctly, it is important that the final application and interpretation of the WASP Index be undertaken by a qualified geohydrologist.

Within the process of selecting a waste site, WASP has a number of different roles and uses, namely:

a. initial site screening - initial site screening and ranking of possible sites can be performed using limited data. The reliability of the data used in the assessment would probably only be of Level 3 or 2;
b. defining the further work to be undertaken after the initial site screening - the initial screening will indicate where data deficiencies and potential problems exist, thus allowing site owners to focus on further work which must be undertaken to adequately evaluate the site with greater levels of data reliability; and
c. final site suitability determination - once detailed field investigations have been undertaken (data reliability levels of 1 or 2) a final site assessment can be made. Sites larger than 30 ha and all hazardous waste disposal facilities would typically require Level 1 data reliability. A final decision regarding the suitability of smaller sites or those sites which are clearly suitable may be taken based on Level 2 data.

During any stage of a site investigation (initial screening through to detailed investigations) WASP can be used to compare a number of possible sites and the sites can be ranked in terms of their suitability.

8.2. Waste site permitting

WASP can be used at various stages in the permit application procedure, described earlier in Section

2.2.4. At the end of the Feasibility study, WASP can be used to make a coarse appraisal of the site's suitability. If the WASP Index indicates that a site is unsuitable, then any further investigation at the site should be discontinued. However, if the information available is unreliable, the permit applicant may continue with further investigations, but the applicant must be informed that, based on geohydrological criteria, doubts about the site's suitability exist. Any further fieldwork must then be undertaken with the full knowledge that the site might be found to be unsuitable. Once more detailed information has been collected, an accurate and final WASP assessment can be made.

In order to ensure uniformity amongst all the Regional Offices of DWAF, it is strongly recommended that WASP assessments be used in all the various stages in the permit application process. This would be in line with procedures followed in other parts of the world. The assessment of site suitability using a standard procedure has been implemented, for example, in Victoria, Australia where a modified Le Grand system is used (Environment Protection Authority of Victoria, 1987). The incorporation of WASP into the permitting procedure would be relatively easy. A slight modification to the current permit application form would be required in order that more information on the Resource Factor can be presented. Further, the carrying out of a hydrocensus during the early stages of site evaluation will have to be promoted. Most of the other information required by WASP is, however, already requested.

8.3. Shortcomings and Limitations

Because of the heterogeneous nature of the geohydrological environment, and the related complexities, some degree of uncertainty exists with all models. Models are merely tools used to make predictions and every effort must be made to ensure that acceptable levels of predictive accuracy are obtained. It must be recognised that WASP, like all methods and models, has some limitations. The limitations largely result from:

a. the assumptions and simplifications used in WASP (Section 5),
b. the testing and validation of the methodology,
c. the accuracy of the data available, and
d. the experience and qualifications of the user of the method.

The procedure has, however, been based on accepted geohydrological principles. WASP attempts to place the most appropriate principles and factors governing site suitability into a scientifically acceptable format and which allows for accurate, consistent and repeatable results to be obtained.

Data manipulation to provide desired results can be achieved using any model. The misuse of the model will certainly tarnish the reputation of the Waste-Aquifer Separation Principle. For this reason, WASP must only be used for assessing the geohydrological suitability of solid waste disposal sites.

WASP cannot, and does not, replace the need for either appropriate field work, suitable data or expert geohydrological input. Even though it is hoped that WASP can promote cost-effective investigation, the appropriate data required will ultimately have to be collected using proper geohydrological investigative techniques.

8.4. Attainment of Project Objectives

The objective of this research project was to (Section 1.2.):

> *develop and field validate a South African-based methodology which addresses the geohydrological components of waste site selection and suitability evaluation*

This objective has been met by the development of WASP and its subsequent verification and validation using waste site permit application data and information collected from 10 well investigated sites spread throughout South Africa. It has been recommended that a follow-up study be initiated in 2 to 3 years time in order that the validity of WASP can be confirmed.

WASP has three main applications (Section 8.1.), namely:

a. initial site screening and planning - only level 3 or 2 data is required for this application
b. setting of data requirements to be obtained from fieldwork
c. final site suitability determination - level 1 or 2 is required.

Initial site screening can be performed using limited data. Once it is decided that the site is feasible and more detailed study is required, WASP can then be used to identify what data is required to make a proper assessment of the site. A final assessment of the suitability of the site can then be performed once all the data are available. The objective concerning the use of the method (Section 1.2.) is accordingly obtained.

It was proposed in Section 4.2. that standardization of site assessment at a national or global level was either failing or difficult to achieve. WASP constitutes the first site evaluation method which is based on South African conditions and considerations and which has been verified, calibrated and validated on quantified site specific data. The site specific method is based on physical factors (Section 5.) which can be quantified using an objective approach. Some subjectivity has to be allowed for to accommodate unique conditions. This is done by means of over-ride factors and specialised geohydrological investigation (Section 7.2.).

The information required by WASP is similar to that presently required in the permit application form. More geohydrological information concerning groundwater usage and groundwater potential is required. The incorporation of these requirements into the permit application form does not constitute a major change. Once the required data are available, WASP is easy to use to determine a WASP Index. The interpretation of the index is straight forward and facilitated by the generalised interpretation table.

A need exists for the technology developed during this research to be transferred to *all* potential users ie. central government officials, municipal officials, privately-owned waste site managers and consultants. The use of WASP enables an indication to be obtained regarding the type of factors which have to be considered in selecting new waste sites, investigation and data requirements for site suitability assessment as well as possible site suitability. It is, however, a requirement that the interpretation of WASP for final decision making be performed by an appropriately qualified and experienced geohydrologist. A course should be presented in order to facilitate technology transfer and promote the use of WASP.

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1. Summary

a. South Africa faces serious water shortages in the future. The development of groundwater resources is regarded as being a partial solution to this growing problem. The disposal of waste on land can pose a significant threat to these resources.

b. The correct siting of waste disposal facilities, in order that waste and aquifers remain separated, is regarded as the only long-term option in protecting viable aquifers from degradation by waste activities.

c. A number of initiatives are currently under way which will promote the protection of groundwater. These include the DWAF waste site permitting drive, the establishment of minimum standards and requirements and research in the waste management and geohydrological fields.

d. It was nonetheless found that no formal or standard approach was being followed in South Africa in the assessment of the suitability of existing or potential sites for waste disposal.

e. A research project was hence undertaken to develop such a method. The project entailed a literature study, an international and local study tours, an evaluation of permit application data, the evaluation of 10 existing waste disposal sites in detail including supplementary fieldwork and drilling as well as the testing of the method using the collected data.

f. A total of 30 different methods were identified which aimed to assess the suitability of sites for waste disposal based on geological considerations. The large number of methods highlighted the universal nature of the problem of correctly siting waste facilities and showed that the concept of standardised evaluation at a national or global level was either failing or difficult to achieve

g. The positive and negative features of these models were examined in terms of type of method, objectives and factors incorporated. After consideration of the objectives of this research and the advantages and disadvantages of the methods studied, it was decided in principle that a weighting and rating approach would be adopted.

h. The separation of waste and aquifers was regarded as the basis for suitability assessment. The method developed was hence called the Waste-Aquifer Separation Principle or WASP. WASP is to be used to assess the suitability of both existing and proposed sites for waste disposal activities based on geohydrological considerations.

9.2. Conclusions

a. Three distinct factors have to be considered in the assessment of site suitability, namely the Threat Factor, the Barrier Factor and the Resource Factor.

b. The Threat Factor defines the threat posed by a particular waste pile and is quantified by means of the relationship between the size of the site and the type of waste to be disposed of.

c. The Barrier Factor is a measure of the ability to keep the waste and aquifer apart. The time that leachate would take to travel from the base of the waste to the top of the aquifer is used for quantifying this factor. It is understood that the longer the time that leachate takes to travel, the greater the leachate attenuation will be, resulting in a corresponding reduction in the threat posed to groundwater resources.

d. The Resource Factor is a measure of the strategic value of a groundwater resource in terms of its use, or potential use. A set of questions which enquire about both groundwater usage and groundwater potential are used in the quantification of this Factor.

e. The WASP Index is determined using the relationship between the three Factors. A nomographic solution is used for this purpose, and until such time that more detailed information are available, linear relationships are assumed.

f. Coupled to each Factor is a data reliability rating. The ratings are in accordance with IEM principles and aim to provide an indication of the detail and accuracy of data used in the assessment. A final data reliability rating is obtained by calculating the average of the Factor data reliability ratings and is recorded behind the final WASP Index in parenthesis.

g. The correctness of WASP was evaluated by comparing the obtained WASP Indices against subjective ratings given to 41 sites around the country. The subjective ratings were based on the researcher's knowledge of the sites and on opinions expressed by people visited during the execution of the project. A close correlation was found. This exercise allowed for a generalised interpretation of the WASP Index to be developed.

h. WASP was validated by comparing geohydrological and groundwater contamination information from 10 well studied waste sites with the obtained WASP Indices. All of the WASP assessments were found to provide accurate and quantitative assessments.

i. It was also established during the evaluation of WASP that the procedure could not account for all situations and that a degree of flexibility was required. In some instances, one consideration was found to dominate the others in terms of a site's suitability and acceptability. Such considerations were termed *over-ride* factors and the use of such factors was hence accommodated in the procedure. In other instances, the uniqueness of a situation required that more specific information were required. Once obtained, this information could be used to motivate the modification of the score of the Factor concerned, or the Index as a whole. The use of both over-ride factors and more detailed specific studies has to be based on data and information with a level 1 data reliability rating.

j. It was concluded that the development, verification and validation of WASP had been based on almost all of the available good quality data and information. Further assessment is not possible until further appropriate data becomes available.

k. WASP provides an accurate and quantitative assessment of site suitability for waste disposal and, if the limitations of the method are respected, it can be used for the purpose for which it was developed.

l. The procedure has three applications namely, initial site screening and ranking, defining further data needs and final site suitability determination. WASP can also be used for the evaluation of sites for permitting purposes.

m. A set of shortcomings and limitations were identified. These are largely related to the assumptions and simplifications required by the method, the testing and validation carried out to date and the accuracy of the data used.

n. The project objectives set out in Section 1.2. have been met in terms of the development of WASP, the applications for which it can be used and the characteristics required of the procedure.

9.3. Recommendations

a. Based on the sound performance of WASP during verification and validation, it was recommended that the use of WASP be promoted.

b. The formal use of WASP in the permitting procedure should be implemented.

c. The inclusion of WASP as a tool in the setting of Minimum Requirements needs to be investigated and promoted.

d. A follow-up study should be commissioned in 2 to 3 years time in order to assess the performance of WASP during it's wider application.

e. A course should be presented in order that WASP be introduced to the geohydrological and waste communities and that these groups be instructed in the use of WASP.

f. With regard to the sites studied in the field, it is recommended that appropriate research monitoring be initiated at Site 5 and Site 10 on a regular basis in order to collect and evaluate valuable contaminant behaviour data. This information will be extremely beneficial during the re-assessment of WASP.

g. It is recommended that this research report be submitted to three or four international leaders in the field of groundwater contamination by waste disposal activities for evaluation and comment.

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APPENDICES

APPENDIX A

Extended Acknowledgements

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APPENDIX B

Short Description of Internationally Used Methods

NAME :	"Formale Erstbewertung" (First Formal Evaluation) Method.
PRINCIPAL REFERENCE :	Department of Water and Wastes, Germany (1992)
TYPE :	Matrix system - the scores from five matrix tables are multiplied by factors to give a final index.
MAIN PURPOSE :	To assess the risk of waste sites to water and the environment.
FACTORS CONSIDERED :	- waste volume and type - thickness and permeability of the vadose zone - distance to built up areas, different groundwater protection zones, and environmentally sensitive areas.
APPLICATION :	Lower Saxony, Germany.
MODIFICATIONS :	
STRONG POINTS :	Simplistic, easy to understand and use. Although simplistic, the use of groundwater protection zones shows that complex geohydrological assessments are included into the framework of the method.
WEAK POINTS :	Does not take into account attenuation potential or leachate generation.

NAME:

PRINCIPAL REFERENCE: Unlu et al. (1992).

TYPE: Mathematic model.

MAIN PURPOSE: Screening for land disposal of petroleum exploration and production wastes

FACTORS CONSIDERED: Waste-zone release sub-model.

- leachate concentration (chloride, total salts, hydrocarbons).

Unsaturated-zone transport sub-model.

- net infiltration rate.
- unsaturated soil permeability.
- dispersion.
- adsorption of organics.
- first order decay.

Saturated-zone transport sub-model.

- horizontal flow.
- three dimensional convective-dispersion transport.

APPLICATION

MODIFICATIONS:

STRONG POINTS:

- Considers sources, pathways and sink.
- Provides quick answer which can be verified with later, more detailed, investigation.
- Is a practical but conservative tool.

WEAK POINTS:

- For a specific type of waste.
- Ignores density driven saturated flow,

NOTES:

- Considers leaching from waste disposal pits and from soils subjected to land-spreading.
- Thickness of unsaturated zone defined by depth between the base of the waste pile to the water table.

NAME:		
PRINCIPAL REFERENCE:	Geological Sensitivity Project Worksgroup (1991).	
TYPE:	Numeric weighting and rating.	
MAIN PURPOSE:	-	to identify areas sensitive to groundwater contamination.
FACTORS CONSIDERED:	-	Time of travel from waste sources to aquifer. - vadose zone thickness. - vadose zone lithology. - vadose zone permeability. - depth to deeper aquifers / confining units.
APPLICATION		- applied in Minnesota, USA.
MODIFICATIONS:		
STRONG POINTS:	-	based on measurable parameters.
	-	the system is quantitative.
	-	the system defines "Levels of work" which implies a degree of accuracy.
	-	the system appears flexible.
	-	based on readily available data (in the USA) such as depth to water, soil and geological maps etc.
WEAK POINTS:	-	the physical and chemical properties of the contaminant are not addressed.
	-	the depth of contaminant introduction is not considered.
	-	the difference in behaviour in the vadose and saturated zones is not considered.
NOTES:		

NAME :	MIRAMOS (Milieukundig Risico-Analyse Model voor Stortplaatsen)
PRINCIPAL REFERENCE :	Goossens (1991)
TYPE :	Mathematical computer model.
MAIN PURPOSE :	A risk analysis model for determining the probability that the amount of percolate moving through an existing landfill will exceed certain minimum allowed limits.
FACTORS CONSIDERED :	- leachate generated (water balance) - potential for failure of the barriers (covering layer, the leachate collection system, the liners, and the vertical barriers). - "correctness" of the design and risk of failure - impacts of failure on the groundwater quality and population health.
APPLICATION :	Netherlands.
MODIFICATIONS :	
STRONG POINTS :	
WEAK POINTS :	Only takes into account engineered conditions - no geological data required. Only suitable for analysis of modern first world sites.

NAME :	SINTACS
PRINCIPAL REFERENCE :	Civita et al. (1991)
TYPE :	Computerized parametric point count (index) model.
MAIN PURPOSE :	The production of aquifer vulnerability maps.
FACTORS CONSIDERED :	- depth to water - actual infiltration - attenuation capacity of the unsaturated zone - types of soil cover - lithology of the aquifer - hydraulic conductivity of the aquifer - slope of the land surface
APPLICATION :	Italy.
MODIFICATIONS :	Based on DRASTIC.
STRONG POINTS :	The weights assigned to each factor vary according to specific conditions ("strings"). Three strings exist - pristine conditions, areas of probable pollution, and karst conditions. The index is converted to a percent of the total possible score.
WEAK POINTS :	Not meant to assess waste sites. Does not assess the pollution risk.

NAME:

PRINCIPAL REFERENCE: Hall and Hanbury (1990).

TYPE: Numeric weighting and ranking.

MAIN PURPOSE:
- to compare and select sites suitable for cemeteries.

FACTORS CONSIDERED:
- Physical aspects.
  - excavatability.
  - stability.
  - workability.
- Sanitary aspects.
  - depth to water table.
  - subsoil permeability.
  - backfill permeability.

APPLICATION Not known

MODIFICATIONS:

STRONG POINTS:
- simple and easy to use.
- provides for over-rides and automatic rejection.
- suffix indicators allows for expansion of numeric index.

WEAK POINTS:
- possibly too simplistic.

NOTES: South African derived method.

NAME: Leaching Potential Index (LPI).

PRINCIPAL REFERENCE: Meeks and Dean (1990).

TYPE: Mathematical equation, using a one-dimension advective-dispersive transport equation.

MAIN PURPOSE:
- to map aquifer vulnerability to pesticide contamination.
- to prioritise monitoring requirements.

FACTORS CONSIDERED:

$$R\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - V\frac{\partial C}{\partial z} - R\lambda C$$

where:

- R = retardation factor (water solubility, organic matter, adsorption coefficient, organic carbon, partition coefficient).
- C = chemical concentration.
- D = hydrodynamic dispersion coefficient.
- V = soil-water seepage velocity (field capacity, hydraulic conductivity, crop type and irrigation practice, evapotranspiration, precipitation).
- λ = first-order decay rate of the chemical in the soil.
- z = vertical depth (water table elevation, land elevation).

APPLICATION: Applied by Meeks and Dean (1990) in San Joaquin Valley, California with success.

MODIFICATIONS: Based on the work of Roa et al. (1985).

STRONG POINTS:
- can be based on existing data or estimations.
- LPI based on governing physical equations and not subjective rankings used in other systems.

WEAK POINTS:
- based on simplifying assumptions.
- does not deal with volatile chemicals which rapidly migrate in a vaporous phase.

NOTES:
- Meeks and Dean (1990) correlated LPI with actual groundwater quality to test validity.

NAME :	Vectorial Approach Method
PRINCIPAL REFERENCE :	Halfron (1989)
TYPE :	A vectorial analysis which uses Hasse diagrams to display the results.
MAIN PURPOSE :	To assess the probability of harm from the presence of pollutants in the environment, according to the site geology.
FACTORS CONSIDERED :	A total of 30 different factors are considered, including: - geological information - hydrological information - hydrogeological information - geochemical information - on-site monitoring - waste characterization and containment - health and safety (30 factors in total)
APPLICATION :	Attempted in Northern USA and Canada
MODIFICATIONS :	
STRONG POINTS :	Does not use indices, therefore allows the relationships and contradictions between different factors to be clearly seen
WEAK POINTS :	Complex to understand and interpret results unless studied in detail.

NAME:	HALO (Hazard Assessment of Landfill Operation) Method.
PRINCIPAL REFERENCE :	Holmes (1989)
TYPE :	Index system, producing scores in seven categories.
MAIN PURPOSE :	Assessment of existing and proposed waste disposal sites.
FACTORS CONSIDERED :	Seven different components are used: - material pollution potential - landfill operators assessment - groundwater pathways - surface water pathways - landfill gas evaluation - impact on receptors - impact on local amenities.
APPLICATION :	United Kingdom
MODIFICATIONS :	
STRONG POINTS :	Very detailed and covers most of the important aspects. Scores per component allows the identification of the problem area.
WEAK POINTS :	Time consuming questionnaires are used.

NAME:

PRINCIPAL REFERENCE: Al-Bakri et al. (1988).

TYPE: Numeric weighting and rating.

MAIN PURPOSE: Initial site screening using exclusion / avoidance criteria. Comparison of potential sites based on measured data.

FACTORS CONSIDERED:

Exclusion / avoidance criteria
Land use
Water resources
Public health
Distance to site

Site comparison
Land:
- topography
- texture of unconsolidated material
- permeability of unconsolidated material
- composition of unconsolidated material
- bedrock depth
- bedrock formation
- bedrock structure

Surface water:
- water bodies
- natural drainage

Groundwater:
- depth to water table
- distance of site to nearest point of water supply
- TDS and water use
- rate and direction of water flow

Ecology:
Climate:
Socioeconomic:

APPLICATION

MODIFICATIONS:

STRONG POINTS:

- Considers selection in a holistic fashion.
- recognises the difference between resources being used and those with potential to be used.
- Is flexible to modification.
- Is easy to use.

WEAK POINTS:

- Is a relative weighting and rating ranking procedure which yields a dimensionless index.

NOTES:

NAME: Groundwater Pollution Risk Assessment.

PRINCIPAL REFERENCE: Foster and Hirata (1988).

TYPE: Graphical technique, based on ratings.

MAIN PURPOSE:
- First step in the evaluation of groundwater pollution risk.
- Prioritise required field investigation.

FACTORS CONSIDERED:
- Contamination load.
  - Class of waste.
  - Intensity of contamination.
  - Mode of disposition.
  - Duration of application.
- Aquifer pollution vulnerability.
  - Groundwater occurrence (type of aquifer).
  - Overall lithology of aquiperm or aquitard (geology).
  - Depth to groundwater or strike (m).

APPLICATION: Latin America and Caribbean.
Presents guidelines on the levels of investigation required.

MODIFICATIONS: Based on *GOD* system proposed by Foster (1987).

STRONG POINTS:
- Based on available data.
- To be used as a guide for planning.

WEAK POINTS:
- Only based on assessment of groundwater pollution risk from man's activities.
- Appears cumbersome to use.
- Does not consider potential of surface water pollution.

NOTES:
- Relates contamination load and aquifer pollution vulnerability to define groundwater pollution risk.

NAME: DRASTIC.

PRINCIPAL REFERENCE: Aller et al.(1987, 1985).

TYPE: Numeric weighting and rating.

MAIN PURPOSE:
- Regional vulnerability mapping.
- Comparison of defined geohydrological settings in terms of relative suitability for waste disposal.

FACTORS CONSIDERED:
- Depth to water (m).
- Recharge (mm/a).
- Aquifer material (geology).
- Soil type.
- Topography (angle of slope).
- Impact on vadose zone (geology).
- Hydraulic conductivity (m/day).

APPLICATION:
- Applied throughout USA eg. Texas (Halliday and Wolfe, 1991), Wisconsin (Zaporozec, 1987).
- Has also been used to define regional monitoring needs (Meeks and Dean, 1990).

MODIFICATIONS:
- Has been modified by a number of authors to meet specific needs eg. Poacher (1989) in Minnesota; Garret et al. in Maine.

STRONG POINTS:
- Can be used to assist in planning of development ie. evaluating impact of land-use on aquifers.
- Can be used to define priority areas for aquifer protection, groundwater monitoring and clean-up activities.
- Can be used as a regional screening tool.
- System designed to use data / information which is readily available (in USA).
- Based on measurable parameters.
- Highly suitable for use with GIS (Halliday and Wolfe, 1991;) or Expert Systems.

WEAK POINTS:
- Is not designed for assessing the suitability of a particular site for waste disposal.
- Ratings for a particular area are often based on regional averages and do not consider local conditions.
- Does not consider pollution sources, mitigatory measures or the potential importance of an aquifer.
- The system is not physically based which leads to subjective scoring (Meaks and Dean, 1990).
- The system does not consider the interaction between wastes with different chemistry nor the physical environment (Meaks and Dean, 1990).

NOTES:
- Gebhardt and Jankowski (1987), when comparing DRASTIC to Le Grand and HELP, found that the method could be used for site-specific study.
- Garret et al. found a poor correlation between DRASTIC and measured contamination levels. They found that DRASTIC did not adequately address fractured rock environments. They also stated

that DRASTIC was a hypothesis which had not been tested.

NAME :	Italian Chromatic Matrix method
PRINCIPAL REFERENCE :	Andreottola et al. (1987)
TYPE :	Series of matrix tables
MAIN PURPOSE :	Assessment of the environmental impact of sanitary landfills
FACTORS CONSIDERED :	Five matrices - cause and impact - impacts and environments effected - potential impact - limiting criteria - residual impact
APPLICATION :	Italy
MODIFICATIONS :	
STRONG POINTS :	Does not require major technical data for analysis
WEAK POINTS :	Difficult to understand and interpret the results.

NAME:	GOD
PRINCIPAL REFERENCE :	Foster (1987).
TYPE :	Empirical system
MAIN PURPOSE :	Assessment of aquifer vulnerability.
FACTORS CONSIDERED :	- groundwater occurrence - overall aquifer class (lithology, grade of consolidation, degree of fracturing and attenuation capacity) - depth to groundwater
APPLICATION :	United Kingdom, Latin America.
MODIFICATIONS :	
STRONG POINTS :	Easy to use, requires limited data.
WEAK POINTS :	Not site specific Does not assess groundwater potential, recharge, or the threat to the aquifer.

NAME : Survey or VOS (Verkennend Onderzoek Stortplaatsen) Method.

PRINCIPAL REFERENCE : Kerkhof et al. (1987)

TYPE : Computer interpretation of questionnaire forms - produces a table of risks for different aspects of the environment.

MAIN PURPOSE : Quick assessment of existing waste disposal sites.

FACTORS CONSIDERED :

- 5 emission factors which describe contaminant production
- the following data are also required by the questionnaire:
  - depth to groundwater
  - nature of the waste
  - site vegetation
  - depth and type of cover material
  - drainage system
  - surface water control
  - geohydrology and groundwater potentials
  - surrounding land use
  - groundwater and surface water use
- 14 migration factors which describe the manner and potential of contaminant movement
- 6 use factors which address the various users threatened by the contaminants.
- assesses risk to the atmosphere, soil, surface water, phreatic groundwater and deeper groundwater.

APPLICATION : Netherlands

MODIFICATIONS :

STRONG POINTS : The separation into the 3 factors allows one to see where the main problems occur.
The results table assesses which of the user environments are threatened.

WEAK POINTS : Time consuming collation of data through questionnaires.

NAME: Pesticide Index.

PRINCIPAL REFERENCE: Roa et al. (1985) (in Canter et al., 1987).

TYPE: Mathematical equation.

MAIN PURPOSE:
- preliminary evaluation of the pesticides to be monitored in groundwater.

FACTORS CONSIDERED:
- Attenuation factor.
  - amount of pesticide entering groundwater.
  - amount of pesticide applied.
  - travel time of pesticide to aquifer.
  - degradation half-life of pesticide.
- Travel time factor
  - distance from soil surface to ground water.
  - retardation factor.
  - volumetric soil-water content at field capacity.
  - net recharge rate.
- Retardation factor
  - soil bulk density.
  - soil organic carbon content.
  - sorption coefficient of pesticide on soil.
  - air-filled porosity of soil.
  - Henry's constant for pesticide.

APPLICATION:
- Used by Khan and Liang (1989) to delineate groundwater pollution potential on island of Oahu, Hawaii (Meaks and Dean, 1990).

MODIFICATIONS:

STRONG POINTS:
- Based on limited data.

WEAK POINTS:

NOTES:

NAME:	HELP (Hydrologic Evaluation of Landfill Performance).
PRINCIPAL REFERENCE:	Schroeder et al. (1984).
TYPE:	Mathematical model, based on the water balance method and SCS runoff method.
MAIN PURPOSE:	- assist designers, reviewers and operators in estimating and minimizing leachate production. - used to define potential risk posed by waste site.

FACTORS CONSIDERED:	- layers within waste pile.
	    - vegetation layer, lateral drainage layer, a barrier soil layer (including liner), waste layers.
	- climatic inputs.
	    - daily precipitation, monthly mean temperatures, monthly mean solar radiation values.
	- hydraulic parameters for the soil.
	    - porosity, field capacity, wilting point, hydraulic conductivity, leakage fraction of liner, runoff.
	- landfill description.
	    - slope, surface area, drainage distance.

APPLICATION:	Applied by Booth and Vagt (1990) in Illinois and Peyton and Schroeder (1987) in various USA states.
MODIFICATIONS:	Is more detailed than the Fenn et al. (1975) method.
STRONG POINTS:	- is widely applicable (Gebhardt and Jankowski, 1987). - is an easy to use design and evaluation tool. - appears to be very comprehensive. - can be expanded to consider contaminant transport.
WEAK POINTS:	- is based on 12 simplifying assumptions. - is based on a water balance approach, which is not valid under arid or semi-arid conditions. - calibration and verification using real data has been limited. - does not consider groundwater.
NOTES:	Peyton and Schroeder (1987) found HELP to be relatively accurate when compared to measured lysimeter leachate flow volumes and rates.

NAME:	Minnesota's Hazardous Waste Siting Criteria (Intrinsic Suitability Flowchart).
PRINCIPAL REFERENCE:	Shilepsky and Pulford (1983).
TYPE:	Flowchart, based on a set of questions.
MAIN PURPOSE:	- Siting of hazardous waste sites on both regional and local scale.
FACTORS CONSIDERED:	- Distance from hydrologic features. - lakes, ponds, rivers, floodplain, wetlands. - Proximity to karst area. - Presence of mass movement problems. - Impact on drinking water resources. - Presence and viability of use of groundwater. - Presence of aquiclude. - Ability to monitor groundwater.
APPLICATION	Method was applied in Minnesota to locate an acceptable hazardous waste disposal facility.
MODIFICATIONS:	
STRONG POINTS:	- The system is easy to use. - the method covers a broad spectrum of siting criteria.
WEAK POINTS:	- the *yes / no* approach may lead to subjectivity.
NOTES:	- this method can easily be incorporated into artificial intelligence systems.

NAME :	Australian Le Grand.
PRINCIPAL REFERENCE :	Kidd and Hancock (1983)
TYPE :	Numerical description.
MAIN PURPOSE:	Evaluation of waste sites.
FACTORS CONSIDERED:	- distance to point of water use - depth to water table - hydraulic gradient - permeability of the subsurface - sorption potential of the subsurface - degree of seriousness of contamination severity - miscellaneous "identifiers".
APPLICATION:	Australia and New Zealand.
MODIFICATIONS :	Modified from Le Grand (1980).
STRONG POINTS :	Takes into account fractured and weathered bedrock occurring at the surface (no soil). Risk to wildlife and recreation also included (not only domestic water use).
WEAK POINTS :	Description is complex and not easily interpreted.

NAME: Hazard Ranking System (HRS) or Mitre Model.

PRINCIPAL REFERENCE: Caldwell et al. (1981) (in Canter et al., 1987).

TYPE: Numeric weighting and rating.

MAIN PURPOSE:

- Ranking facilities for remedial action according to risk to health and the environment.
- Prioritization of sites for inclusion into Superfund program.
- Selecting new waste disposal sites.
- Define potential of uncontrolled waste site to cause health or safety problems and / or ecological and environmental problems.

FACTORS CONSIDERED:

- Route characteristics (ground water, surface water, air).
- Migration.
  - containment.
  - route characteristics.
    - depth to aquifer, net precipitation, permeability of the unsaturated zone.
    - slope of site, 1 year 24 hr return rainfall, distance to nearest surface water user, flood potential.
  - waste characteristics.
    - physical state, persistence, toxicity.
    - volatility, reactivity, incompatibility, toxicity.
  - hazardous waste quantity.
    - total waste quantity.
  - targets.
    - groundwater use, distance to nearest well down-gradient of site, population served by groundwater within a 3 mile radius.
    - surface water use, distance to sensitive environment, population served by surface water within a 3 mile radius.
    - distance to nearest human population, population within 1 mile radius, distance to sensitive environment, land use.
- Fire and explosions.
    - accessibility.
    - containment.
    - waste characteristics.
    - targets.
- Direct contact.
    - accessibility.
    - containment.
    - waste characteristics.
    - targets.

APPLICATION

- Used by US EPA for drawing up priorities list for Superfund Program.
- Evaluated by Wu and Hilger (1984) - they found the method to be expedient and consistent but requires considerable information.

MODIFICATIONS:

STRONG POINTS:

- Large number of factors considered.
- Allows for an assessment of factor interaction.

WEAK POINTS:

- Very complex as it covers a very broad evaluation of the environment.
- US Centre for Risk Management found a poor correlation between the results of the method and risk levels later determined.
- The HRS places great value on population factors at the expense of other worthy considerations eg. potential for future groundwater usage (Wu and Hilger, 1984).
- The method does not adequately cover the impact on surface water resources (Wu and Hilger, 1984).
- The interaction between the waste and the environment is not addressed eg. solubility of leachate in relation to migration (Wu and Hilger, 1984).
- The toxicity rating of various chemicals seems to be out of balance (Wu and Hilger, 1984).
- Waste quantities have a big impact on the final result.
- Groundwater factors are limited.
- All groundwater is considered as a resource and potable.

NOTES:

- Developed by the US EPA.
- Based on route of exposure (groundwater, surface water, air).

NAME: Brine Disposal Methodology.

PRINCIPAL REFERENCE: Western Michigan University (1981) (in Canter et al., 1987).

TYPE: Numeric weighting and rating using a flowchart.

MAIN PURPOSE:
- Assessing groundwater contamination potential from oil and gas field brine disposal.
- Defining groundwater quality monitoring needs.

FACTORS CONSIDERED:
- Method of brine disposal.
- Volume disposed of.
- Subsurface geology.
  - vertical isolation or depth to water table.
  - thickness of shale.
- Oil and gas well density.
- Proximity to water wells.
- Density of water wells.

APPLICATION:

MODIFICATIONS:

STRONG POINTS:
- Simplistic to use.

WEAK POINTS:

NOTES:

NAME: Site Rating Methodology (SRM).

PRINCIPAL REFERENCE: Kufs et al. (1980) (in Canter et al., 1987).

TYPE: Numeric weighting and rating.

MAIN PURPOSE:

- assessing contamination potential from existing and proposed waste sites.
- defining information needs and priorities.
- defining remedial actions and priorities.

FACTORS CONSIDERED:

- Rating Factor System : for rating the general hazard potential of a site.
  - receptors.
    - population size, distance to nearest well, land use, critical environments.
  - pathways.
    - evidence of contamination, level of contamination, type of contamination, distance to surface water, depth to groundwater, net precipitation, soil permeability, bedrock permeability, depth to bedrock.
  - waste characteristics.
    - toxicity, radioactivity, persistence, ignitibility, reactivity, corrosiveness, solubility, volatility, physical state.
  - waste management practises.
    - site security, hazardous waste quantity, total waste quantity, waste incompatibility, use of liners, use of leachate collection systems, use of gas collection systems, use and condition of containers.
- Additional Points System : for modifying the general rating based on site-specific problems.
  - factors that are not properly addressed in Rating Factor System eg. hazard caused by power lines running through the site, guidance is given relating to weighting of additional factors.
- Scoring System : interpreting the ratings in meaningful terms.

APPLICATION Used to prioritise Superfund sites for remedial action.

MODIFICATIONS:

STRONG POINTS:

- Based on readily available data and site visits.
- The system provides both relative and absolute hazard rankings.
- System is flexible and allows the inclusion of other factors.

WEAK POINTS:

NOTES:

NAME: Le Grand (1980) Method.

PRINCIPAL REFERENCE: Le Grand (1980)

TYPE: Numeric weighting and rating.

MAIN PURPOSE:
- used for evaluating groundwater sensitivity to contamination at waste sites.

FACTORS CONSIDERED:
- distance to point of water use.
- depth to water table.
- water table gradient.
- permeability.
- Sorption.
- degree of confidence.
- miscellaneous identifiers.

APPLICATION: Applied by Kidd and Hancock (1983) in Australia and was found to be readily applicable.

MODIFICATIONS: Modified by Marin et al. (1989) to form a computerized screening tool.

STRONG POINTS:
- used at individual sites and based on measured point data.
- includes a confidence indicator based on data accuracy.
- considers both contamination and hazard.
- is more rigorous than DRASTIC.
- based on readily available data and can be applied with minimum data.
- can rank sites from best to worst based on contamination potential.

WEAK POINTS:
- workers need a large amount of experience with the rating code before it can be readily understood.
- difficult to rank intermediate sites.
- method considers each site to be an independent variable and does not consider interaction.

NOTES:
- The fact that the method can be applied by people with minimal technical ability is by no means a strong point - strange results obtained from the method could be explained on this basis.

NAME: Surface Impoundment Assessment (SIA).

PRINCIPAL REFERENCE: Silka and Swearingen (1978).

TYPE: Numeric weighting and rating.

MAIN PURPOSE:
- To rate the contamination potential of groundwater from surface impoundments.
- To rank the contamination potential of groundwater from different surface impoundments.
- Used to define monitoring priorities.

FACTORS CONSIDERED:
- rating of groundwater contamination potential.
  - thickness of unsaturated zone.
  - nature of unsaturated zone material.
  - relative hazard of the waste.
  - quantity and quality of underground resource (groundwater availability).
- rating of relative magnitude of potential endangerment to current users of groundwater drinking sources.
  - type of water source (surface or groundwater).
  - flow direction of water source.
  - distance between contamination source and resource.
- miscellaneous identifiers.
- scores combined in last step.

APPLICATION
- First-round estimation.
- Applied by Sammy and Canter (1980) throughout the USA.

MODIFICATIONS: Based on Le Grand (1964) and Le Grand and Brown (1977) systems.

STRONG POINTS:
- Can be based on estimations or precise parameter values.
- Each data input is given a confidence level.

WEAK POINTS:
- Based on many generalizations.
- Final rating difficult to interpret and no guidelines are presented to define whether a particular site is suitable or not.
- Silka and Swearingen (1978) do not describe how the monitoring priorities are defined nor applied.

NOTES:
- Resources must be protected for present and future usage.
- Canter (1985) notes that vadose zone and groundwater quality ratings resulted in the biggest difference in scores.

NAME:	Landfill Site Rating or Le Grand-Brown method.
PRINCIPAL REFERENCE:	Le Grand and Brown (1977) (in Canter et al., 1987).
TYPE:	Numeric weighting and rating.
MAIN PURPOSE:	- Comparative evaluation of potential landfill sites. - Prioritizing the groundwater pollution concerns of existing landfills within a geographic area.
FACTORS CONSIDERED:	- Distance from contamination source to nearest well or point of water use. - Depth to the water table. - Gradient of the water table. - Permeability and attenuation capacity of the subsurface materials through which the contaminant is likely to pass.
APPLICATION:	Used by van Tonder and Muller (1991).
MODIFICATIONS:	Modified to form SIA method.
STRONG POINTS:	- Uses simple and easy to measure parameters. - Is site specific.
WEAK POINTS:	- Code is difficult to understand and difficult to compare.
NOTES:	

NAME: Waste - Soil - Site Interaction Matrix.

PRINCIPAL REFERENCE: Phillips et al. (1977)

TYPE: Matrix

MAIN PURPOSE:

- Assessment of industrial and liquid waste disposal on land.
- Comparative evaluation of potential waste disposal sites.
- Prioritizing the groundwater pollution concerns of existing landfills within a geographic area.

FACTORS CONSIDERED:

- Waste factors.
  - effects.
    - human toxicity.
    - ground water toxicity.
    - disease transmission potential.
  - behavioural.
    - chemical persistence.
    - biological persistence.
    - sorption.
    - viscosity.
    - solubility.
    - acidity / basicity.
  - capacity rate.
    - waste application rate.
- Site of potential waste application factors.
  - soil.
    - permeability.
    - sorption.
  - hydrology.
    - water table.
    - gradient.
    - infiltration.
  - site.
    - distance between site and user.
    - thickness of porous layer.

APPLICATION Used in Oklahoma to evaluate the impact of septic tanks.

MODIFICATIONS:

STRONG POINTS:

- clearly states which are acceptable sites and which are not.

WEAK POINTS:

NOTES:

NAME: Site Rating System (SRS).

PRINCIPAL REFERENCE: Hagerty et al. (1973) (in Canter et al., 1987).

TYPE: Numeric weighting and rating.

MAIN PURPOSE:
- Comparing potential waste disposal sites.
- Evaluating environmental pollution potential of existing sites.

FACTORS CONSIDERED:
- Soil.
  - infiltration potential.
  - bottom leakage potential.
  - filtering capacity.
  - adsorptive capacity.
- Ground Water.
  - organic content.
  - buffering capacity.
  - potential travel distance.
  - ground water velocity.
- Air.
  - prevailing wind direction.
  - population factor.

APPLICATION

MODIFICATIONS:

STRONG POINTS:

WEAK POINTS:

NOTES:

NAME: Le Grand (1963) Method.

PRINCIPAL REFERENCE: Le Grand (1963).

TYPE: Numerical weighting and rating.

MAIN PURPOSE:
- preliminary evaluation of the potential for groundwater contamination from waste disposal sites.

FACTORS CONSIDERED:
- Depth to water table.
- Sorption (based on geology / soil type).
- Permeability (based on geology / soil type).
- Water table gradient.
- Distance to point of use.

APPLICATION

MODIFICATIONS: Later modified to form the Le Grand (1984) method and SIA method.

STRONG POINTS:
- suitable for quick initial appraisal where geologic and hydrologic data are scarce.

WEAK POINTS:
- method should not be used to evaluate sites which disposed of mixed wastes.
- limited geological descriptions, only really covers unconsolidated sediments.

NOTES:

APPENDIX C

Waste site permit applications and reports evaluated

in order to obtain WASP methodolgy

quantification and verification data

List of waste site permit applications and reports evaluated in order to obtain WASP model quantification data

DWAF HEAD OFFICE	**TRANSVAAL REGION**	**HIGHVELD REGION**
Aloes SWDS	Alldays SWDS	Brakpan Mines SWDS
Chloorkop SWDS	Arnot Power Station	Bullfrog Pan SWDS
Holfontein SWDS	Brits SWDS	Daggafontein SWDS
Koedoesklook SWDS	Delmas SWDS	Dobsonville SWDS
Margolis SWDS	Eersterus SWDS	Jambee Quarry SWDS
Mossgas SWDS	Haenertburg SWDS	Lottering SWDS
Vaal Power Station	Hartbeespoort SWDS	Marie Louise SWDS
Umbogintwini SWDS	Hendrina Power Station	Natfield Spring SWDS
Vissershok SWDS	Kempton Park SWDS	Platkop SWDS
	Linbro Park SWDS	Robinson Deep SWDS
	Middleburg SWDS	Rooikraal SWDS
	Midrand SWDS	Secunda SWDS
	Marble Hall SWDS	Union Fireclay SWDS
	Northern Site SWDS	Viljoenskroon SWDS
	Nylstroom SWDS	
	Onderstepoort SWDS	
	Pelindaba SWDS	
	Pietersburg SWDS	
ORANGE FREE STATE REGION	Randburg SWDS	
	Rayton SWDS	
	Roosespruit SWDS	
	Schoemansville SWDS	
	Soshanguve SWDS	
Bloemfontein North SWDS	Western Platinum SWDS	
Bloemfontein South SWDS	Witbank SWDS	
Freegold South SWDS	Zandfontein SWDS	

List of waste site permit applications and reports evaluated in order to obtain WASP model quantification data (continued)

WESTERN CAPE REGION	EASTERN CAPE REGION	NATAL REGION
Afdak SWDS	Addo Langbos SWDS	Ballengeigh SWDS
Atlantis SWDS	Arlington SWDS	Bisasar Road SWDS
Bellville Park SWDS	Bontrug SWDS	Bulbul Drive SWDS
Bellville South SWDS	Bushmans River Mouth SWDS	Escourt SWDS
Citrusdal SWDS	Kareedouw SWDS	Eskom Ingagane SWDS
Coastal Park SWDS	Kilian Brickfields SWDS	Inanda SWDS
Darling SWDS	Martins SWDS	Magabeni SWDS
Everite-Brackenfell SWDS	Mistkraal SWDS	Mooi River SWDS
George SWDS	Patensie SWDS	Mpumalanga SWDS
Gwaing SWDS	Queenstown SWDS	New England Road SWDS
Ladismith SWDS	St Francis Bay SWDS	Port Edward SWDS
Malmesbury SWDS	Sunlands SWDS	Port Shepstone SWDS
Noordhoek SWDS	Tarkastad SWDS	Rietvallei SWDS
Robertson SWDS		SA Crushers Quarry SWDS
Swartklip SWDS		Shongweni SWDS
Upington SWDS		Tugela Mill SWDS
Vissershok SWDS		Umbumbulu SWDS
Worcester SWDS		Umlazi SWDS

APPENDIX D

Short Description and Findings of Waste Sites Studied in Detail

SITE 1

Solid Waste Disposal Site

Location:	Western Cape
Climate:	Winter rainfall region which experiences an average rainfall of 465 mm/a. The corresponding potential evaporation is 1613 mm/a.
Water resources:	The town relies entirely on groundwater resources for water supply. Two wellfields are used to abstract approximately 6 million m^3/a. A surface water scheme, requiring an extensive pipeline, could be developed should groundwater not be capable of meeting demand in the future. Such a scheme would, however, be costly.
Waste disposal:	The site was brought into operation in 1975 and closed in 1988. Domestic waste and "clean" industrial waste (textiles, paper, cardboard) was disposed of at the site. The site covers an area of approximately 6 ha.
Geology:	The waste disposal site is located on unconsolidated Cenozoic sediments which overlie the Tygerberg Formation of the Malmesbury Group. The sands, which constitute the regionally significant primary aquifer, attain a thickness of 20 m in the vicinity of the waste site.
Geohydrology:	The geohydrology of the area has been extensively studied and monitored. As a result it is fairly well understood. The waste disposal site is located approximately 6,5 km up-gradient of one of the wellfields. The vadose zone, comprising of well sorted, clean, quartz aeolian sands and sporadic lenses of calcrete and peat, is 1,77 m thick (highest water level monitored in winter months). A K of between 1 and 25 m/d was determined by means of aquifer tests while values ranging between 13 and 35 m/d were determined using double-ring infiltrometer tests. Porosity has been estimated using a number of different techniques, with an average of 30 % appearing realistic. The aquifer itself has been well demarcated into recharge zones and production zones. An extensive monitoring and management system is used to continually re-evaluate the safe yield of the aquifer. Background water quality is good with EC typically less than 100 mS/m. The water is usually of a NaCl type. In the vicinity of the waste site, all ionic constituents fall within recommended SABS domestic drinking water standards (background water quality sample).
Discussion:	Monitoring was instituted at the site during 1989. A set of 8 shallow wellpoints, monitored quarterly, is used to observe groundwater quality changes. Significant contamination has been detected down-gradient of the site (see Figure 1). It was estimated that the plume is advancing at a rate of approximately 40 m/a. It is pertinent to note that, even in this permeable aquifer, contamination was only detected about 14 years after the site was brought into operation.

The waste site has had an impact on the quality of the groundwater system. Even though the site is relatively small, significant leachate is generated during the winter months. The permeable vadose zone allows for rapid infiltration and limited attenuation. The underlying aquifer can thus be easily contaminated. For this reason, the site is unsuitable for waste disposal.

At this particular site, however, sufficient distance exists between the site and the wellfield to assume that dilution will render the plume less harmful. It is thus not expected that the waste site will impact on the groundwater resources in the short term. Should the site continue producing leachate in the long-term, contamination at the wellfield could theoretically occur.

Site suitability: In light of the relatively small threat posed by the waste pile and the distance between the site and the wellfield area, it would appear that the site is suitable for waste disposal. The vadose zone however offers little protection in terms of attenuation. The site is nonetheless located within the primary aquifer and as such, it would be unwise to operate a waste disposal facility in the area in the future.

Information: The aquifer has been well studied, particularly by CSIR and DWAF, over the last 20 years. Continual exploration, evaluation and monitoring has resulted in a good understanding of the geohydrological system to be developed. Information concerning the waste sites was obtained from annual monitoring reports and permit application documentation. A permit is not required for the site as it was closed prior to 1989.

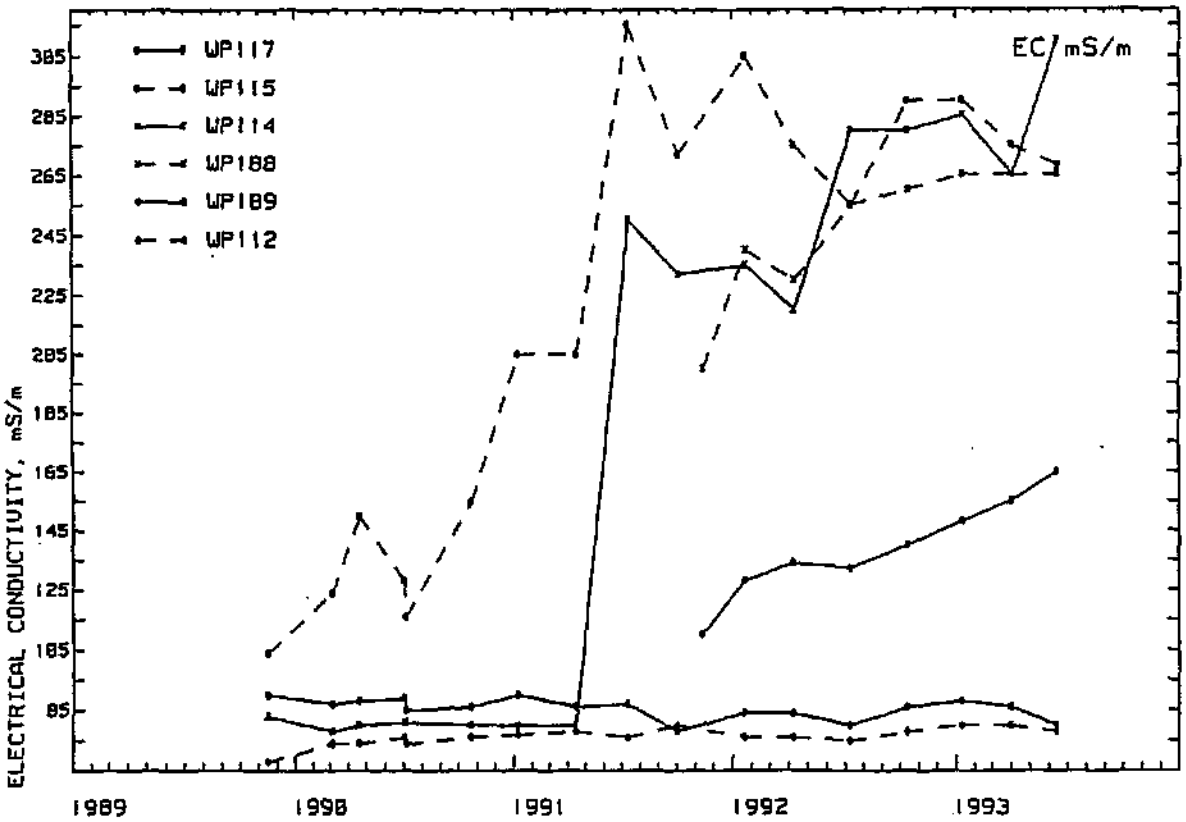


Figure 1: Results of monitoring at Site 1 - EC trends

SITE 2

Waste Disposal Site

Location:	Western Cape
Climate:	Winter rainfall region which experiences an annual average rainfall of 244 mm/a. The corresponding potential evaporation is 4 000 mm/a.
Water resources:	The town obtains its water supply from two dams located in the surrounding mountains. The present water supply will be sufficient for the town for at least the next 30 years. A large irrigation dam is located near the town which could be used to supply water during droughts. Groundwater is not considered as a viable water source for the town. An extensive but locally significant aquifer exists some 5 km to the west of the waste site. This resource is used for agricultural purposes.
Waste disposal:	The site was brought into operation in 1987 and has an expected lifespan of about 50 years. Household domestic waste, garden waste and building rubble form the major portion of deposited waste. Periodic disposal of asbestos, veterinary compounds and animal carcasses as well as "stookwyn" liquid also takes place. The total site covers an area of 16 ha.
Geology:	The waste disposal site is located on conglomerates of the Enon Fm of the Uitenhage Group. The formation attains a minimum thickness of 41 m. The nature of the hard rock below was not accurately identified owing to the geological complexity of the area.
Geohydrology:	A conceptual hydrogeological model of the site is presented in Figure 2. The so-called upper aquifer comprises of sediments of the Enon Fm. A shallow clay layer results in a perched water table. The winter high water level was measured at 1,6 m. K for the clay layer was determined from a set of double-ring infiltrometer tests, to be 0,003 m/d while that of the Enon Fm was set at 0,3 m/d. The yield of a 41 m deep borehole drilled at the site was measured to be 0,06 L/s. The water quality from the upper aquifer is extremely poor, with EC being in the order of 3 000 mS/m (the EC of leachate was measured to be 790 mS/m). The water is NaCl type and has a pH ranging between 6 and 7. This saline water is typical of the Enon Fm. in the area, as found during other investigations in the general region of the waste disposal facility. No boreholes or groundwater usage was found within a 1 km radius of the site. A primary aquifer to the west was extensively investigated by DWAF. This aquifer is separated from the Enon Fm by distance, lithological changes and a major river which flows between the two hydrogeologic units.
Discussion:	Monitoring was instituted at the site during 1991. The network consists of 2 boreholes and 6 stacks of pressure vacuum lysimeters (PVL) set to depths of 2 m and 8 m respectively. From the monitoring preformed, contamination of groundwater by leachate from the waste pile could not be identified.

However, flushing effects caused by the winter rain were clearly evident in the deeper boreholes, indicating that recharge of subsurface water bodies does occur. The shallower PVL's did not show a similar pattern, thus pointing to recharge occurring by lateral inflow beneath the clay layer.

A negative impact on the groundwater system caused by waste disposal has not been recorded. Further, the ambient poor quality suggests that the Enon Fm. could never be used as a water resource. If anything, the leachate improves the water quality. In addition to the poor quality, the hydrogeological conditions encountered at the site are not favourable for groundwater resource development. More favourable conditions are found to the west of the site.

Site suitability

Due to hydrologic and geohydrologic conditions encountered, it is not expected that the site will have an impact on any water resources in the area. From a geohydrological viewpoint, the site appears to be well situated.

Information:

Hydrological and hydrogeological investigations have been undertaken in the immediate area around the site by DWAF and DWAF-appointed consultants. Further a number of DWAF and WRC funded geohydrological investigations have been carried out in the general region. The CSIR undertook a groundwater research project at the waste site while the municipality has gone to great efforts (study tours and literature study) to develop a proper sanitary landfill site. The waste data was provided by the municipality. This is a permitted waste site.

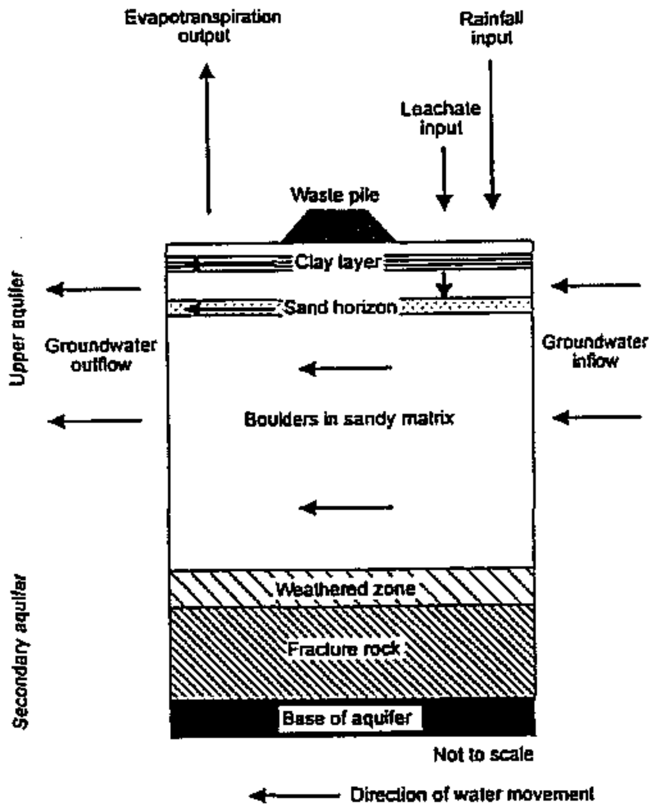


Figure 2: Conceptual hydrogeological model of Site 2.

SITE 3

Waste Disposal Site

Location: Eastern Cape

Climate: Rain falls throughout the year. Annual average rainfall is 667 mm/a while the corresponding potential evaporation is 1 700 mm/a.

Water resources: The city obtains its water supply from three dams located some distance to the west. Owing to prolonged drought and continual water shortages, a surface water scheme which pipes water to the city from a major river in an adjoining catchment is currently being constructed. Even though geological units, which are recognised to have high water-bearing characteristics, exist in the area, groundwater has mostly been excluded as a possible urban water source.

Groundwater is abstracted from a regionally significant aquifer and is used to supply water to a nearby town. It is also extensively used by the agricultural sector. The groundwater resources in the immediate vicinity of the waste site are, however, limited.

Waste disposal: The site was brought into operation in 1973 and has an expected lifespan of about 35 years. The site accepts toxic and hazardous industrial liquid wastes while solid waste is disposed of in a nearby Class II site. The final size of the site is expected to be in the order of 15 ha. Area for the expansion of waste disposal activities does, however, exist.

Geology: The waste disposal site is located on weathered mudstone and shales of the Cretaceous Sundays River Formation. The sediments were deposited under marine conditions and, based on the results of oil exploration drilling carried out near the waste site, the formation has a thickness of about 1 800 m. The clays are of a Ca montmorillonite nature which are regarded as "swelling" clays.

Overburden, consisting of soils, sands and gravels with intermittent calcrete lenses - belonging to the Bluewater Bay and Alexandria Formations - are also found at the site. This unit attains a thickness of approximately 2 m. However, in most areas within the boundaries of the site, the sediments have been removed for road building.

Geohydrology: From laboratory tests, K of the shales was measured to be in the order of 8×10^{-6} m/d (see Figure 3). Laboratory tests have also set porosity at between 10 and 20 %.

Groundwater flow direction appears to mimic topography. Rest water levels could only be obtained days after the boreholes were drilled. As such, the water obtained in the boreholes was referred to as "seepage"water. The shallowest recorded water level at the site was 5,0 m.

As far as could be ascertained, no groundwater is used within 2 km of the waste site. A major Table Mountain Group aquifer exists within the region. This aquifer is on the upthrown side of the Coega fault, located approximately

7 km to the north, while the waste site is located on the downthrown side. From the hydrogeological research work performed, the two areas are not in hydraulic continuity.

Groundwater quality measured at the site is extremely poor, with TDS ranging between 10 000 and 30 000 mg/L. The water typically displays a NaCl character. Such quality is characteristic of the Sundays River Formation in the vicinity of the site.

Twelve monitoring stations have been installed at the site. Water samples are collected regularly. To date no contamination has been identified.

Site suitability: From a geohydrological perspective, the waste site appears to be well situated. The extremely poor ambient groundwater quality, coupled with the poor transmitting capabilities of the Sundays River Fm., indicate that:

- no usable aquifers exist within 2 km of Site 3, and
- the leachate from the site will be contained.

Further, the waste site does not pose a threat to the major Table Mountain Group aquifer.

Information: Numerous geotechnical and hydrogeological investigations have been undertaken at the site by BL Wiid and Steffen, Robinson and Kirsten. Extensive geohydrological studies in the region have been carried out by DWAF. Two M.Sc. theses have resulted from the work as well as a number of B.Sc. (Hons.) theses. The geology of the area has been well investigated by the local university and Soekor. Hydrological investigations have also been undertaken by, amongst others, Rhodes University, U.P.E and CSIR. Information pertaining to all aspects of the site and waste disposal were provided by the site owners (e.g. permit application documentation, an Environmental Impact Control report, a Site Design report and a Site Operating report). An application for a Class I permit has been submitted to DWAF.

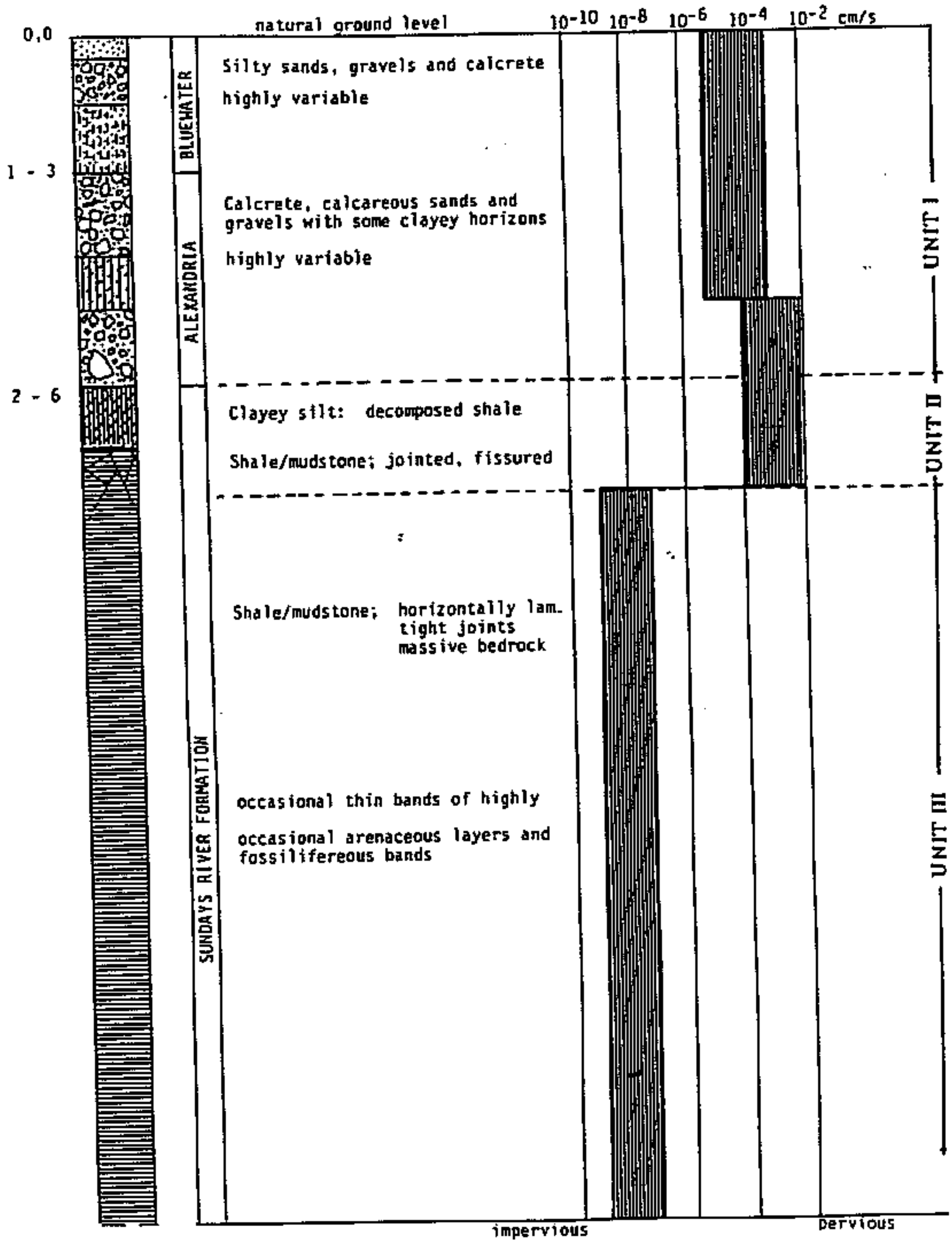


Figure 3: Generalised schematic geological profile of Site 3.

SITE 4

Waste Disposal Site

Location: PWV Region - Transvaal

Climate: The area falls within the summer rainfall region with most of the rain occurring as afternoon thunderstorms. Annual average rainfall is 689 mm/a while the corresponding potential evaporation is 1 700 mm/a.

Water resources: The water supply of the PWV region is well documented and falls largely under the control of the Rand Water Board. The development of the Lesotho Highlands Water Supply Scheme to augment existing water sources is also well known. The town closest to the waste disposal site currently obtains water from the Rand Water Board. Owing to the success of conjunctive surface and groundwater use by two nearby municipalities (economic and otherwise), the town is currently investigating the economic and technical feasibility of developing a regionally significant dolomitic aquifer. The aquifer occurs within the municipal boundaries.

Dolomitic aquifers in the area are used to supply water to the private, industrial and agricultural sector. A total of 40 boreholes were located in the vicinity of the facility during a hydrocensus carried out in 1985. Usage of the aquifer and the potential for aquifer development is thus well established.

Waste disposal: A worked brickfields clay quarry was used for disposal. The site was brought into operation in 1986 and was closed in 1991. The site was used to dispose of industrial effluent and domestic waste types. The size of the site is 7 ha.

A number of pits have been, or are still being, worked. It is thus possible that these pits could be considered as future disposal facilities.

Geology: The waste disposal site is located on a Karoo outlier located in dolomitic formations of the Transvaal Sequence. The area has been intruded by regionally extensive dykes and sills of both pre- and post-Karoo age. The geology in the immediate vicinity of the waste site is extremely complex and heterogeneous owing to:

- faulting, micro-fracturing and slump structures within the Ecca Group sediments,
- the irregular upper surface of the dolomites of the Chuniespoort Group (Figure 4),
- the intrusion of dykes and sills, and
- modern land subsidence and sinkhole formation.

Geohydrology: The regional hydrogeology has been extensively investigated and, based on assessments of exploitation potential, the aquifer is recognised as a regionally significant aquifer. The dolomitic aquifers can be used as sole source water sources, used to augment existing water supply and / or drought relief supply. At present, two municipalities obtain 9,2 and 1,9 million m^3/a respectively from compartments 1,5 km directly down-gradient of Site 4. A spring located 1,8 km down-gradient of Site 4 flows at 2,4 million m^3/a. It is expected that a third municipality will also develop the groundwater resources of these inter-linked compartments in the near future.

Five boreholes were drilled in the immediate vicinity of the site. Yields ranged between 0,1 and 6 L/s. Even though the obtained yields are well below the proposed production borehole yield standard of 25 L/s, the area is still an integral part of an important aquifer system.

Ambient groundwater quality is excellent with EC being less than 70 mS/m. The dolomitic water is readily distinguishable from water originating from other rock types and contaminated groundwater by its $CaMg\text{-}HCO_3$ nature. The detailed hydrogeological investigation at the waste site revealed that 3 boreholes had been contaminated by waste disposal activities. Contamination resulted in slightly higher Na levels and significantly higher Cl and SO_4 levels. The EC recorded in one of the contaminated boreholes rose from 60 mS/m in 1990 to 205 mS/m in 1992. A number of boreholes reflected low levels of contamination, caused by general urbanization.

Rest water levels at the site were measured to be between 11 m and 13 m beneath the base of the waste facility. Regional flow directions have been well defined. Flow in the vicinity of the site appears to be both NW and NE, as opposed to the regional N direction. These local deviations are probably the result of aquifer heterogeneity reflected by residual gravity low zones.

By the very nature of the hydrogeological properties of dolomitic formations, K can vary considerably over short distances. T values reported range from 1 to 13 700 m^2/d. A T of 790 m^2/d was determined by means of an aquifer test near the waste disposal site. This equates to a K of approximately 45 m/d. K values for the Karoo sediments were determined by means of both field and laboratory experiments. The field determinations yielded estimates of between 0,8 m/d and 0,2 m/d. The laboratory estimations yielded much lower values.

The hydraulic continuity between the Karoo sediments and dolomitic formations has not yet been established. Geological logs, water level data, hydrochemical data and isotope studies point to hydraulic continuity, but the evidence is still inconclusive.

The isotope data collected at the site suggests that active groundwater flow only occurs in the upper 20 m of the saturated zone. A mean residence time of hundreds of years was determined for samples collected at depths of 60 m. Samples collected at 100 m and deeper yield estimates measured in thousands of years. The shallower water, which was described as "very recent water", had residence times of less than 25 years.

Discussion: The potential to develop dolomitic groundwater resources for urban water supply purposes is well established. The vulnerability of the aquifers is also recognised. Protection from existing and potential contamination sources is thus needed. With respect to Site 4, groundwater contamination by waste disposal activities has been identified. Further, the development of the aquifer in the immediate vicinity of the waste site is currently under review.

Even after extensive geohydrological investigation of the PWV dolomites and detailed investigations at the waste facility, a number of uncertainties still exist with respect to using Karoo outliers for waste disposal activities. The effectiveness of the argillaceous sediments to act as a buffer between the waste and the resource remains in question. Transmissive zones are indicated by faulting, micro-fracturing and slump structures within the outlier. Preferential flow paths also exist at the contact between dykes and sills and the host country rock. Modern land subsidence and sinkhole formation further impact on the hydraulic properties of the various geological units.

It has not been possible to prove that the Karoo rocks are not in hydraulic continuity with the dolomitic aquifer, even after in-depth geohydrological investigation. This inability should lead to serious misgivings arising with regard to the practise of using these geological features for waste disposal.

Site suitability: The use of Karoo outliers in dolomitic formations appears to be problematic. The preferential flow paths resulting from fracturing and faulting indicate that the barrier zone is not effective in keeping the waste (and leachate) separate from groundwater resources. Further, based on geological and geohydrological considerations and the large number of uncertainties which still exist regarding the waste disposal facility, Site 4 must be regarded as unsuitable for waste disposal activities.

Information: Regional hydrogeological investigations have been undertaken by DWAF and DWAF-appointed consultants. These investigations also considered the large amount of available geological information. More detailed and localised studies have been conducted by CSIR and WLPU. The waste site itself has been investigated by BL Wiid (for the site owners) and the Atomic Energy Corporation in collaboration with the University of the Witwatersrand (as part of a WRC-funded project). The waste site owners provided information concerning the history of the site. A permit application for the site has, as yet, not been submitted to DWAF.

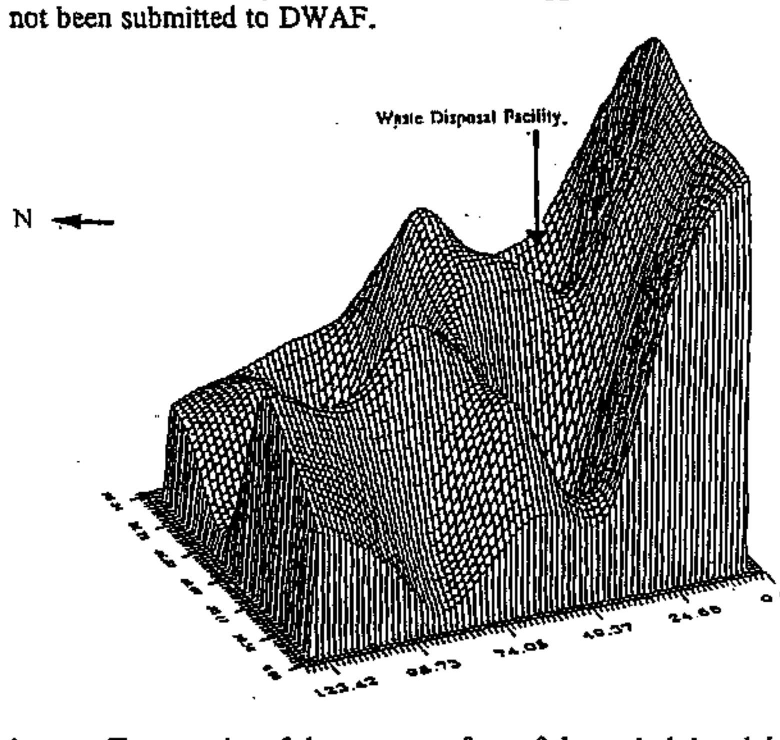


Figure 4: Topography of the upper surface of the underlying dolomite.

SITE 5

Waste Disposal Site

Location:	Eastern Cape
Climate:	The region receives rainfall throughout the year and experiences an average rainfall of 465 mm/a. The corresponding potential evaporation is 1 613 mm/a.
Water resources:	The small town initially obtained water from the Churchill Dam via a 16 km long pipe line. Wellpoints were used to augment this supply during peak demand periods. Continual problems with the wellpoints (apparently mainly of a technical nature) and a rapidly growing water demand led to a search for further water sources. An expansion of the pipeline proved to be not feasible owing to the high costs involved and the unreliability of the dam (particularly during periods of drought). Exploration of the Table Mountain Group showed that a major aquifer existed which was capable of meeting average and peak demand. Two wellfields have been in operation since 1989 and the aquifer has demonstrated itself to be reliable. Water quality is good but contains some iron and has a encrusting nature.
Waste disposal:	The site was established in 1985 and is used to dispose of domestic waste, building and garden rubble and raw sewage. The domestic waste is disposed of in trenches and regularly burned. When full the trenches are covered. Building and garden rubble is deposited on top of the covered trenches. The garden rubble is also regularly burned. Raw sewage is pumped from conservancy tanks and deposited within the boundary of the site. Depositional patterns are governed by seasonal holiday influxes during December and April. The site at present covers an area of approximately 4 ha.
Geology:	The waste disposal site is located on unconsolidated Recent windblown sand deposits and Cenozoic sediments which overly the Table Mountain Group. The sands, which constitute an integral part of the regional aquifer system, attain a thickness of 40 m in the vicinity of the waste site.
Geohydrology:	The geohydrology of the area has been extensively studied and monitored. As a result it is fairly well understood. The waste disposal site is located approximately 700 m down-gradient of one of the wellfields. Monitoring of water levels in the wellfield boreholes has shown that hydraulic gradients can be reversed during periods of prolonged abstraction. The vadose zone, comprising of fine to medium grained, clean, quartz aeolian sands with sporadic lenses of calcrete and silcrete, is approximately 3 m thick. A K of between 6 and 18 m/d was determined by means of falling-head and constant-head percolation tests. A porosity of 20 % is assumed. The aquifer appears to be regionally extensive. Two wellfields have been developed to supply the town with water. The upper primary aquifer is in hydraulic connection with the lower fractured rock system. Monitoring of the aquifer and abstraction takes place in order to allow for the continual re-evaluation of the aquifer.

Background water quality is good with an EC of 100 mS/m being typical. The water is usually of a NaCl type. The water in the primary aquifer, however, tends towards a $CaCO_3$ or recent recharge type. In the vicinity of the waste site, the water falls within recommended SABS domestic drinking water standards (background water quality sample). The water does, however, tend to have a high Fe content.

Discussion:

Four boreholes were drilled at the waste site. Three boreholes were drilled to the base of the primary aquifer (40 m) and yielded between 5 and 7 L/s. The forth borehole was only drilled to 20 m but still yielded 2 L/s.

Stratified monitoring of EC was performed in all boreholes (Figure 5). Significant groundwater quality stratification was identified with the base of the stratified zone corresponding to a laterally extensive calcrete layer overlying a fine-grained brown sand layer containing peat material. Further, the upper poor quality water is chemically different from the underlying water. The contaminated water tends towards a $CaSO_4$ type with an elevated EC. EC of the upper contaminated water is approximately 40 % higher than the lower waters. From this evidence, it is apparent that the contamination plume primarily flows in the upper zones of the primary aquifer.

An aerial analysis of the groundwater quality data revealed that the lower part of the primary aquifer had also been contaminated. EC levels are higher than recorded elsewhere during the groundwater exploration studies. Background levels range between 80 and 120 mS/m, while at the waste site levels range between 240 and 140 mS/m. It would thus appear that, with time, the plume could impact on the whole aquifer system.

It is difficult to distinguish whether the contamination is a result of waste disposal, sewage disposal or both. Elevated ammonia and phosphate levels support sewage contamination while the $CaSO_4$ shift could result from leachate from domestic waste. Because of the small size of the site and the fact that the pollution impact can already be identified (within 5 years), it is assumed that the sewage disposal has had a far greater impact than the domestic waste.

The data from SW 4 can be used to show that the rate of upper plume migration is greater than 30 m/yr. No estimation can be given for the lower zone. It is interesting to note that SW 1 did not yield ambient groundwater quality information. It is postulated that the regional hydraulic gradient is reversed during pumping of the Santa wellfield. The lateral extent of plume migration was not defined.

Site suitability:

Even though the site is relatively small, the disposal of waste and sewage poses a real threat to the groundwater system. The permeable vadose zone allows for rapid infiltration and limited attenuation. The underlying aquifer, the existence of which is well established, can thus easily be contaminated. Even though the site is located down-gradient of the wellfield, it is still possible for the plume to migrate northwards towards the wellfield. Groundwater abstraction could result in the reversal of hydraulic gradients. Based on geohydrological considerations, the site is regarded as unsuitable for waste disposal.

Information: The water supply to the town was previously investigated by Ninham Shand and Haldyn Klein and Associates. Geohydrological exploration was performed by both DWAF and SRK. SRK assisted in the aquifer development and carried out the on-going routine monitoring. Information concerning the waste site was obtained from the Town Clerk and Municipal officials. Geohydrological work was carried out at the site by CSIR as part of this research project. The site has not been permitted.

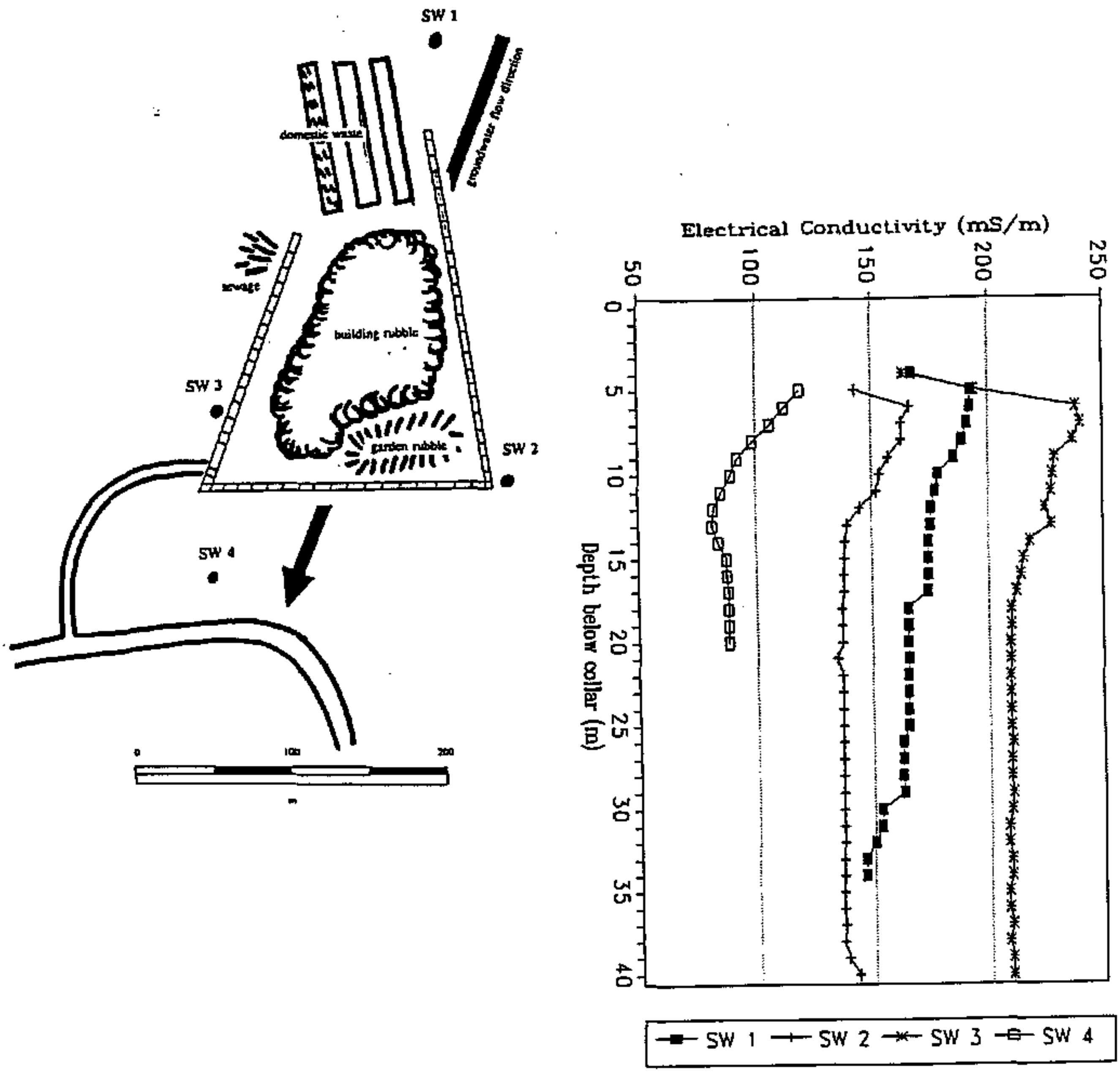


Figure 5: Stratified EC sampling in boreholes at Site 5.

SITE 6

Solid Waste Disposal Site

Location :	Eastern Cape
Climate :	Summer rainfall area which experiences an annual average rainfall of 440 mm, occurring predominantly as thunderstorms. Annual evaporation is in the order of 1 500 mm.
Water Resources :	The town relies totally on groundwater for its water supply. Initially an aquifer located 1 km from the town, and adjacent to the waste site, was exploited (boreholes TD 17 and TD 20 in Figure 6). During 1993 a new groundwater scheme was developed some 10 km north of the town. The boreholes adjacent to the waste site are still used in conjunction with the new scheme and account for 50 % of total groundwater abstracted for municipal supply. Surface water resources have been shown to be too costly to develop.
Waste disposal :	The waste disposal site adjacent to the town water supply boreholes was closed during 1991 after about 18 years of use. All waste was burnt, with limited covering taking place. Since the site was closed, the waste is now disposed of in an old quarry approximately 800 m from the previous site. The old site covers an area of approximately 1 ha and accepted mostly household waste. No industries are located in the town.
Geology :	The waste site is sited over a dolerite dyke, which has intruded into Beaufort Group shales and sandstones. The dyke dips to the west. The upper levels of the shales are weathered. The soil horizon has a maximum thickness of 4 m.
Geohydrology :	The aquifer adjacent to the waste site is related to the dolerite dyke intruding into Beaufort Group sandstones and is recharged by the nearby river and dams. Boreholes drilled into the dyke - shale contact zones did not produce yields with exploitable volumes. Boreholes drilled away from the dyke were also low yielding. Sustainable borehole yields appeared to be a function of distance from the nearby non-perennial river (ie. the further the distance from the river, and major source of recharge, the lower the sustainable yield) and intersecting the dyke - sandstone contact. Groundwater quality was good, with EC varying between 74 and 92 mS/m. The vadose zone underlying the site consists of weathered shales and clays, grading into fresh shales with increasing depth. The south-western corner of the site is underlain by the dolerite dyke which was first intersected at a depth of 3 m. Water levels recorded in October 1993 varied between 14 and 20 m. After the substantial rains which fell between September and January and which broke the drought, piezometric levels rose to 6,36 m below surface. Down-the-hole permeability tests showed that hydraulic conductivity for the 10 m thick unsaturated zone ranged between 1,3 and 0,05 m/d. These are regarded as maximum values related to the most permeable fractures. Double-ring infiltrometer tests undertaken in the surface soil produced hydraulic conductivities of 0,001 m/d.

Discussion : Expectations were that boreholes drilled into the dyke contact zone would be high yielding. During the investigation this was not always found to be the case. High yielding holes were associated with the dyke - sandstone contacts and distance from the river. The boreholes drilled into the dyke - shale contact adjacent to the site yielded less than 0,1 L/s.

Measured K values of the unsaturated zone were higher than expected. No measurement of K were made for the weathered shale horizons. The K of this zone, regarded to be the most impermeable, is thus not known.

Results of the groundwater sampling showed that some limited deterioration in quality had taken place. The 3 up-gradient boreholes (Nos 1, 2 and 4) had EC values of 77, 70, 76 mS/m respectively while the down-gradient holes (Nos 3, TD 17 and TD 20) yielded respective values of 96, 97 and 82 mS/m. It was also found that there was an improvement in the groundwater quality with distance away from the site in a down-gradient direction. Even though some deterioration in water quality had taken place, SABS maximum limits had not been exceeded. The degree of quality changes was about 30 %. Based on the available information, it was concluded that the waste site has definitely had an impact on groundwater quality in the vicinity of the site.

Site Suitability: The site has caused a deterioration in the quality of water from a borehole used to supply the town with water. The original decision to close the site by DWAF thus appears to be justified. The fact that the site has had an impact on a sole source aquifer renders the site unsuitable for waste disposal.

Information : The site has been extensively investigated by the Directorate of Geohydrology of DWAF. The geohydrological investigation undertaken during this study encompassed a hydrocensus, geophysics, infiltration tests, drilling of four boreholes and groundwater sampling of all boreholes in the area. A permit application for the site has, as yet, not been submitted to DWAF.

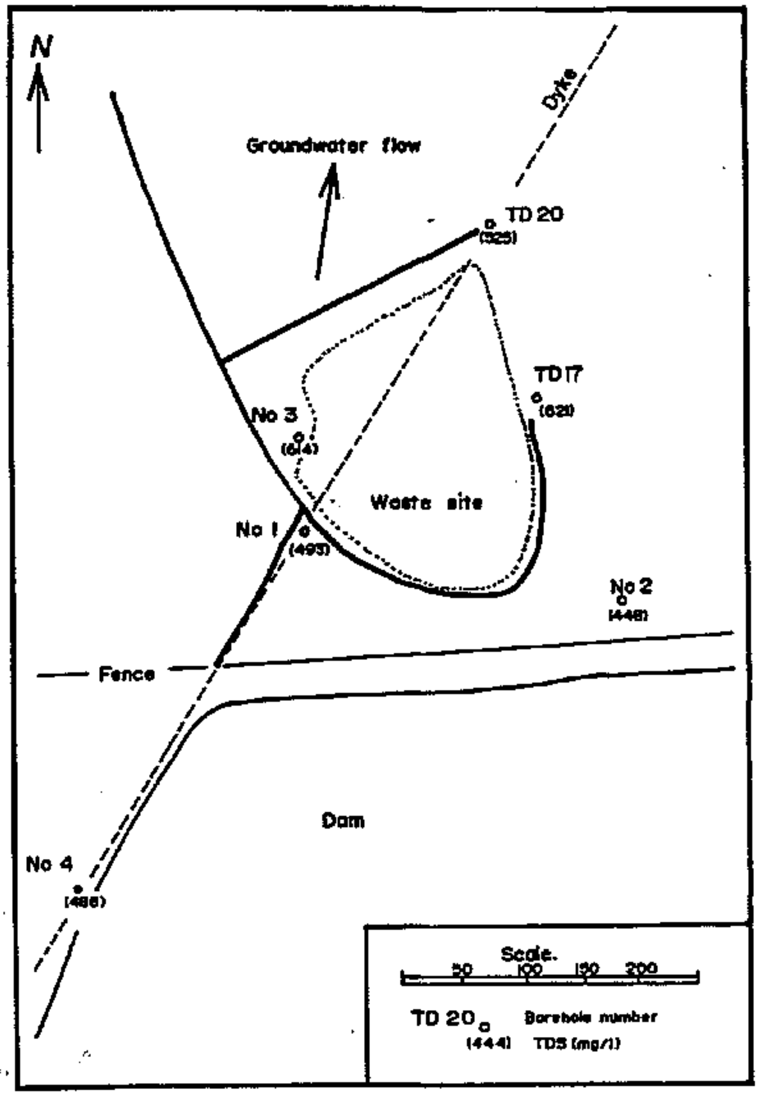


Figure 6: Position of town water supply boreholes (TD 17 and TD 20) and research boreholes in relation to the position of the waste site and dolerite dyke.

SITE 7

Solid Waste Disposal Site

Location : Eastern Cape

Climate : The area falls in the summer rainfall zone and experiences an average annual rainfall of 540 mm/a, occurring predominantly as thunderstorms. The evaporation rate is approximately 1 600 mm/a.

Water Resources : The town obtains it's water from the Bongola Dam. Groundwater usage occurs sporadically throughout the town and is used for irrigation of gardens and sports fields. A municipal by-law prevents groundwater from being used for drinking purposes. A number of garden irrigation boreholes were located in a suburb near the waste site.

Waste disposal : The waste site has been in operation for at least 8 years. The site is located in an abandoned road works quarry, covers an area of 1,5 ha and is over 8 m deep in places. At present, the domestic waste is compacted and covered on a daily basis, although cover material is not freely available. The site accepts approximately 150 m^3 of domestic waste daily.

Geology : Shales and sandstones of the Beaufort Group are exposed in the quarry. A large dolerite sheet is found 500 m to the north of the site while a dolerite sheet was intersected at a depth of 20 m in the irrigation boreholes in the suburbs to the south of the waste facility.

Geohydrology : The geohydrology of the area has been extensively studied by DWAF and is relatively well understood. Yield of the borehole used for irrigation in the suburb located to the south of the site ranged typically between 1 and 3 L/s, although yields as high as 15 L/s were reported. The borehole closest to the waste site was located some 500 m to the south of the site.

Most aquifers are very localised and are associated with dolerite - sandstone contact zones or zones of folding. None of these conditions were encountered during the drilling at the waste sites. Boreholes drilled were either "dry" or yielded less than 0,1 L/s. However, a few days after drilling seepage water was found in all the boreholes. The water level varied between 12 and 16 m below surface, with the shallowest recorded level being 12,14 m.

The vadose zone underlying the waste site consists of moderately weathered shales grading with increasing depth into fresh shales. Down-the-hole permeability tests showed K to range between 0,015 and 0,0078 m/d. These K values are regarded as typical of the most permeable fractures zones. Double-ring infiltrometer tests undertaken in the surface soils produced a K of 1,2 m/d.

Ambient groundwater quality was reported to be good with EC being less than 100 mS/m.

Discussion: Evidence of groundwater contamination was found (Figure 7). Water quality of boreholes located down-gradient of the site was found to be almost double that of up-gradient boreholes. The suitability of the site thus has to be considered in terms of the strategic value of the aquifer.

Site Suitability: The threat posed by the waste pile is small. The use of an old quarry has, however, undoubtably increased the possibility of leachate seeping into the groundwater system via preferential pathways. In effect, the barrier zone has been mined out. The fact that a deterioration in the groundwater quality has been detected supports this. Whether the contaminated groundwater would affect qualities of the aquifer in the nearby suburb down-gradient of the site is a matter of conjecture. It is likely that some degree of attenuation would take place, thus limiting the impact of contamination. The value of the groundwater is questionable, especially in light of the water only being used for garden irrigation. Other more suitable groundwater target zones exist around the town. The site would thus be considered to be largely acceptable.

Information : The general area has been extensively studied by DWAF, but little geohydrological work has been done in the immediate vicinity of the waste site. During this study, the following geohydrological work was carried out: a hydrocensus; geophysics; infiltration tests; drilling of 4 boreholes and groundwater sampling of all holes in the area. A permit has not yet been applied for.

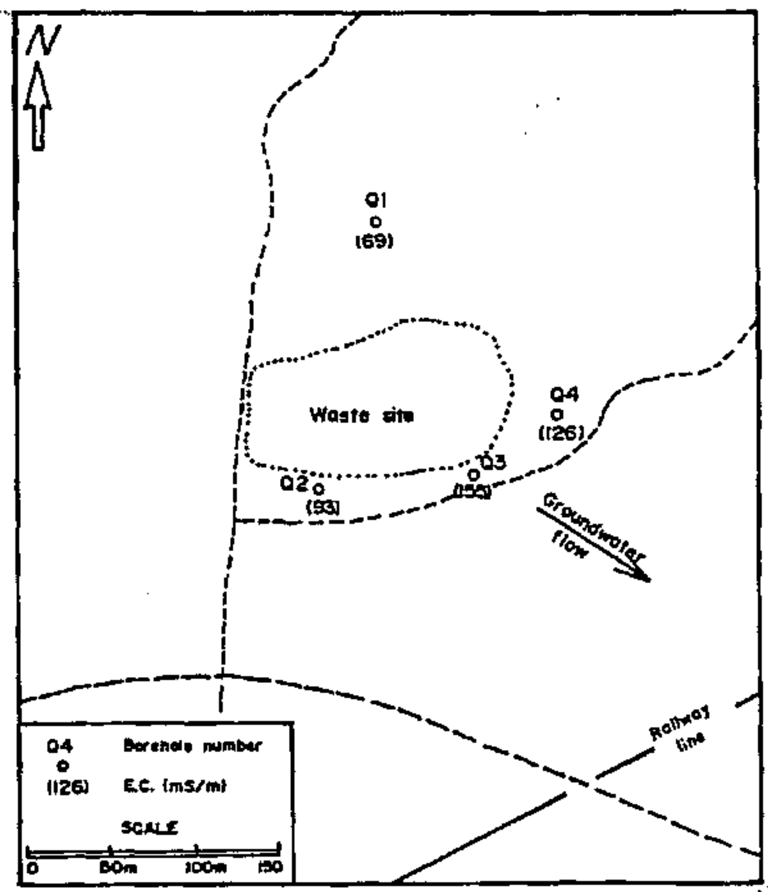


Figure 7: Position of boreholes at Site 7.

SITE 8

Waste Disposal Site

Location:	Natal
Climate:	Summer rainfall region which experiences an annual average rainfall of approximately 1 000 mm/a with a corresponding potential evaporation of 1 300 mm/a.
Water resources:	The city relies entirely on a sophisticated network of surface water resources for water supply. The township surrounding the waste facility is also linked to this network. No evidence of groundwater usage was recorded in a 2 km radius around the site. In terms of the greater area around the site, groundwater is not widely used and is, at this stage, limited to irrigation use.
Waste disposal:	The site was brought into operation in 1988 and is expected to be closed by 1998. Both domestic waste and industrial (liquid and solid) waste is disposed of at the site. Approximately 10 % of the waste is classified as "hazardous." The site covers an area of approximately 15 ha. A leachate collection system has been installed at the toe of the landfill with the collected leachate being sent to a nearby sewage works for treatment.
Geology:	The waste disposal site is located at the head of a valley on unconsolidated Berea Red sands. These deposits have a thickness ranging from 30 m to 0 m across the site. At the base of the valley, unconsolidated alluvial sand deposits are found. The unconsolidated deposits in turn overlay arenaceous Natal Group Sandstones, glacial Dwyka Tillite and argillaceous Pietermaritzburg Formation Shales. An east-west trending fault, with a throw of some 300 m, transects the site.
Geohydrology:	The geohydrology of the area has not been widely studied. The presence of Natal Group Sandstones and the east-west fault and the good quality of the groundwater, however, point to the presence of a viable groundwater resource. Depth to groundwater varies considerably as a result of topography (Figure 8). At the head of the valley, depth to water was measured to be 29,00 m below surface. This also corresponds to the Berea Red sands / Natal Group sandstone contact. Further down the valley, a water level of 1.76 m was measured. Groundwater flow direction is controlled by topography and thus flows from east to west, towards the Isipingo River. Due to the large differences in depth to water, it was difficult to define the thickness of the unsaturated zone. A vadose zone thickness beneath the waste pile of 2 m is thus assumed. The permeability of the fractured and jointed hard rock formations was measured to range between 0,3 and 0,00006 m/d. This wide range is typical for fractured environments. The permeability for the unconsolidated sediments was reported to be in the order of 0,01 m/d. The fact that the water table coincides with the sand / hard rock contact indicates that the basal zone of the sand horizon is relatively permeable.

Little information is available regarding borehole yields. All monitoring boreholes at the site yielded less than 1 L/s but yields in excess of 15 L/s have been recorded at boreholes drilled into fractured Natal Group sandstones.

The ambient quality of the water monitored is moderate, with EC ranging between 80 and 130 mS/m. The water is of a NaCl type and is fit for direct human consumption.

The availability of surface water in the region has resulted in limited groundwater development. In recent times, the lower cost of groundwater resource development, as opposed to surface water development, has led to more attention being paid to this resource. The Natal Group sandstones are regarded as potential targets for groundwater development.

Discussion:

The waste site is located in the middle of a major third-world township and borders a cemetery. Both of these land uses could impact significantly on any underlying aquifer and the Isipingo River located in the valley. The now closed landfill site next to the Mangosuthu College of Technology is not, however, expected to have an impact in the immediate vicinity of Site 8.

The waste disposal site poses a significant threat in terms of the size and nature of waste deposited. This is supported by the volume of leachate captured in the collection system and the leachate seen oozing from the waste body. Further, it would appear that the vadose zone has a limited capability in terms of separating the waste from groundwater bodies. The permeable zone at the base of the Berea Red sandstone does, however, allow a portion of the leachate to move laterally. This would therefore pose a threat to the river.

From the monitoring performed at the site, it is evident that leachate has contaminated the groundwater. As very limited quality stratification with depth was recorded, it must be assumed that the leachate has penetrated into the aquifer and that the contamination is more than a near surface phenomenon. This contamination has occurred relatively quickly when compared with other cases of detected groundwater contamination.

The one mitigating factor against the site being recorded as a poor site, is that it is surrounded by other sources of contamination ie. third-world housing and a cemetery. It is likely that any groundwater resources in the area could not be developed due to contamination that has, or will, result from these two land uses.

Owing to the relatively high volume of leachate produced at the site, some form of engineering would be required. The engineering would be aimed at collecting the leachate for treatment such that the contamination remained within the vicinity of the waste facility.

Site suitability:

Based on the other existing groundwater contamination sources which prevail in the immediate vicinity of the site, the waste site is suitable for waste disposal activities. Some form of engineering would, however, be required to collect leachate. The possible impact of the waste facility on the Isipingo

River also needs to be considered.

Information: A detailed geological and geohydrological report was prepared for the owners of the waste facility by Davis Lynn & Partners. An Environmental Impact Control report was prepared by Lombard & Associates. A motivation report, submitted as part of the permit application, was also compiled by the owners. A permit has been applied for and the application is in the process of being evaluated by DWAF.

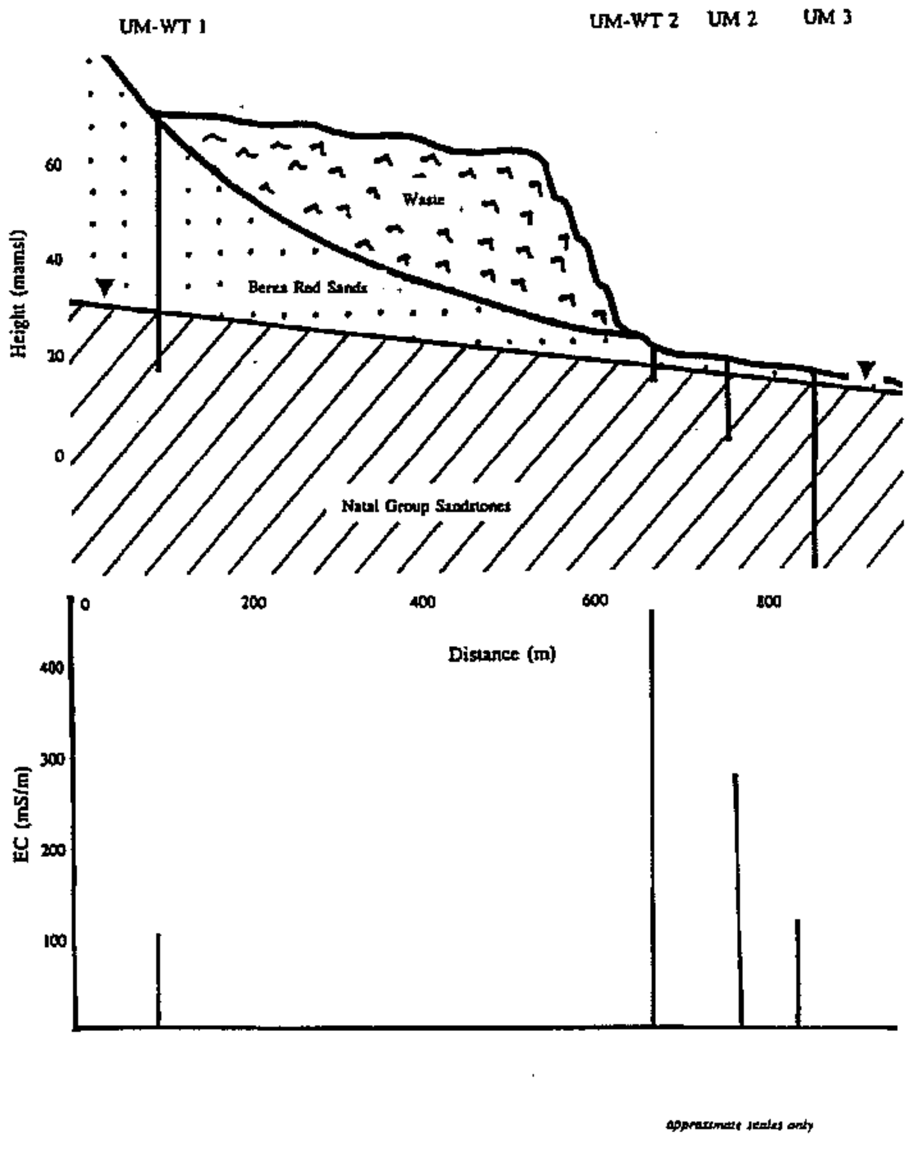


Figure 8: Recorded groundwater contamination at Site 8.

SITE 9

Solid Waste Disposal Site

Location:	Natal
Climate:	The site is located in a summer rainfall region which experiences an annual average rainfall of 850 mm/a. The corresponding potential evaporation is 1600 mm/a.
Water resources:	The town is supplied by water from the Durban - Pinetown - Pietermaritzburg water supply network. Groundwater is not widely used at present owing to sufficient surface water resources.
Waste disposal:	The site was brought into operation in 1952 and has thus been in use for approximately 40 years. Plans are currently afoot to re-engineer the site in such a way that it has a remaining lifespan of approximately 15 years. At present the relatively flat site covers an area of approximately 30 ha. Typical urban domestic waste is deposited at the site as well as small quantities of liquid waste and some sewage sludge.
Geology:	The waste disposal site is located on shales of the Pietermaritzburg Formation of the Karoo Sequence. A thin alluvial cover, which attains a maximum thickness of 6,5 m, is found in the areas adjacent to the Msunduzi River. Dwyka Tillite and dolerite of Jurassic age is also found in the vicinity of the waste site.
Geohydrology:	The geohydrology has not been studied in detail and is thus not well understood. As far as could be ascertained, no groundwater usage takes place within the immediate environs of the waste facility.

The site is located in the floodplain of the Msunduzi River. The river, which flows in an easterly direction, forms a northern boundary for the site while the Blackburrow Spruit bounds the site in the south and east (Figure 9).

As would be expected near a major river, the groundwater level is near surface. A depth to water of 4,40 m was recorded during November 1993. Earlier measurements of less than 1,0 m had, however, been reported for the area southeast of the waste site. The vadose zone thus comprises of the alluvial material. It was also proposed that the river system is in direct hydraulic continuity with the groundwater bodies.

A K value of 0,08 m/d was presented for the silty sand alluvial material while a porosity of 20 % is assumed. A general absence of deep seated fractures and joints in the hard rock formations was also noted. All four research boreholes drilled at the site were either "dry" or yielded "seepage" water at a rate of less than 0,5 L/s.

The groundwater quality can be described as good, with EC ranging between 80 and 120 mS/m. Three groupings of groundwater were made on a basis of EC (80 mS/m, 110 mS/m and 150 mS/m), but no clear distinction could be made on the chemical nature of the groundwater. Significant stratification was only recorded in one borehole and this is thought to be lithologically controlled. Samples collected from old monitoring stations east of the site had an EC of 60 mS/m. Based on available hydrochemical data, no contamination of any form could be detected.

Discussion: The geohydrological regime at the waste site is extremely complex owing to the interaction between the groundwater regime, the Msunduzi River and the Blackburrow Spruit. A far more detailed study than that performed will be required to gain a reasonable understanding of the dynamics of the system.

The inability to detect any form of groundwater contamination could be ascribed to the flushing effect of water from the river recharging into the groundwater body. Further, contamination of the surface water bodies would also be difficult to detect as the input of leachate would be small in comparison with the volume of river flow ie. the leachate would be diluted to such an extent that changes in concentration would be minuscule. Indications of contamination of the Blackburrow Spruit and the Msunduzi River were, however, reported during the earlier investigations.

A number of potential contamination sources exist in the area. Historically, land farming of sewage, night soil and hazardous industrial effluent and sludge was carried out in the general area south and east of the waste site. A major sewage works has subsequently been constructed about 1 km to the east of the site. A major third world township and squatter community is located just north of the Msunduzi River. Further, the waste site has been in existence for over 40 years.

Insufficient reliable geohydrological information is available from which to make a proper evaluation of the suitability of the site. Using what information is available and a number of assumptions, it would appear that, from a geohydrological point of view, the site is acceptable. The geology of the area indicates that a major aquifer does not exist in the vicinity of the site and that no groundwater is used. The fact that no contamination could be detected, with the given number of possible contamination sources and the duration of their existence, must be considered as mitigatory circumstances.

The siting of this site, however, needs to be considered in terms of its impact on the hydrological environment. Waste sites in this area are known to produce large amounts of leachate while the Msunduzi River flows into the storage dams of the Durban - Pinetown - Pietermaritzburg water supply network.

Site suitability: The waste site poses a significant threat in terms of size and type of waste discarded while the vadose zone has limited attenuation capabilities. The groundwater potential of the area appears to be small and a number of other potential sources of pollution exist in the area. The site would therefore be considered suitable, but the impact of the waste site on surface water resources needs to be appraised.

Information: Limited geohydrological work has been carried out in the area. Preliminary geological, geotechnical, geohydrological and hydrological investigations were carried out by Drennan Maud and Partners and Ninham Shand for the owners of the site. An Environmental Impact Control Report was also compiled for the site by Lombard and Associates, supported by AA Loudon & Partners and Hill Kaplan Scott. This is a permitted site.

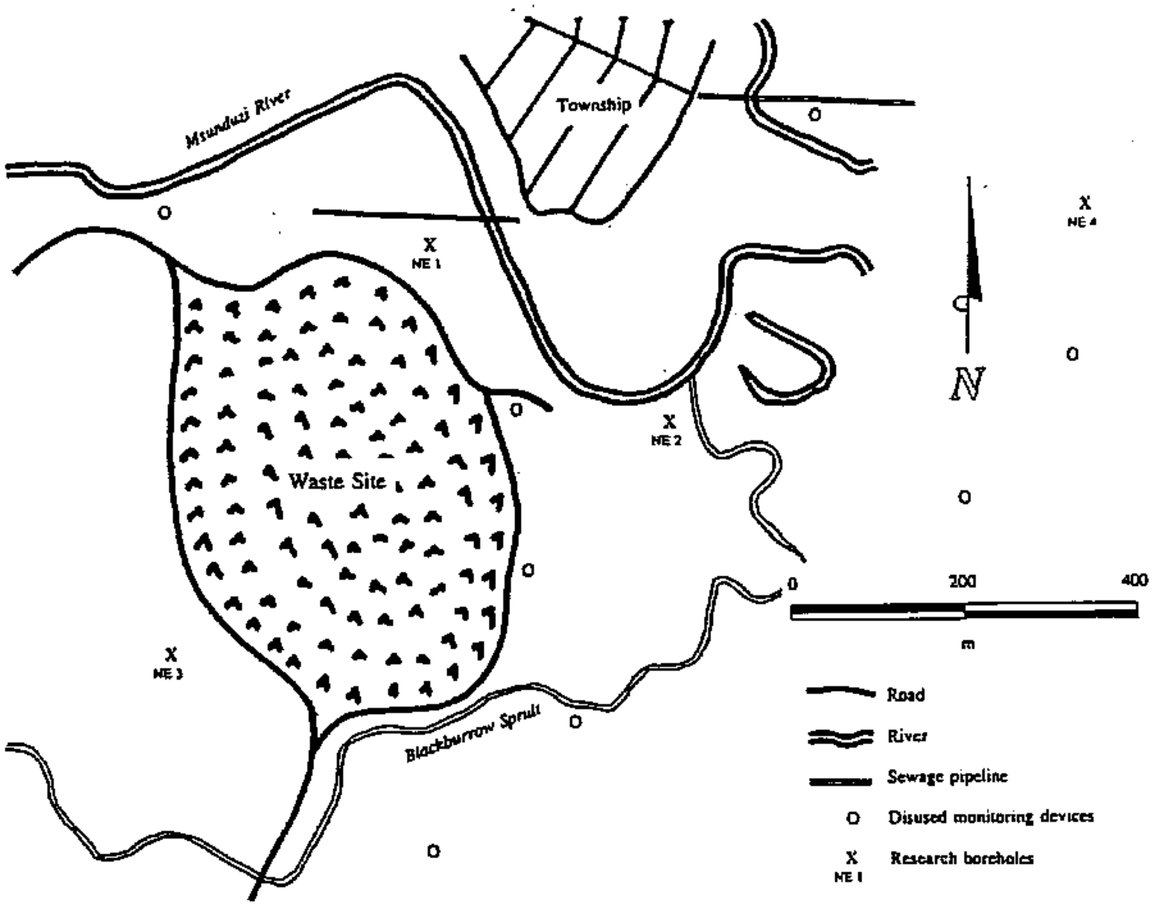


Figure 9: Hydrological features at Site 9.

SITE 10

Waste Disposal Site

Location:	Natal
Climate:	Summer rainfall region which experiences an annual average rainfall of approximately 1 000 mm/a with a corresponding potential evaporation of 1 800 mm/a.
Water resources:	The city relies entirely on a sophisticated network of surface water resources for water supply. Groundwater is only used on a local scale for irrigation purposes. During the drought of the 1980's, the sandy aquifer adjacent to the site was used for drought relief purposes. The sandy aquifer is associated with the alluvial deposits of the Mgeni River floodplain and is laterally extensive.
Waste disposal:	The regional site was brought into operation in 1980 and has an expected remaining lifespan of some 10 years. Mainly domestic waste and garden rubble is disposed of. Some industrial and commercial waste is also disposed of at the site. The site covers an area of approximately 25 ha. A leachate collection system was installed at the toe of the site, but during site visits it was found that the system no longer worked and was in a state of disrepair.
Geology:	The waste site is located in a steep sided, north facing valley on the edge of the Mgeni River floodplain. The site is located on black carbonaceous shales of the Pietermaritzburg Formation of the Ecca Group. Dolerite dykes and sills of Jurassic age have intruded into the area. Northeast - southwest striking faults are located directly east and west of the site, the most prominent of which is the Springfield Fault. Smaller structural features are also evident in the vicinity of the waste site.
Geohydrology:	Little detailed information is available concerning the geohydrology of the area. It would, however, appear that two distinct groundwater units exist, namely the fractured hard rock unit and the primary sandy aquifer associated with the floodplain.

The hard rock aquifer comprises black carbonaceous shales of the Pietermaritzburg Formation. The shales owe their water bearing properties to fracturing associated with the faults and dolerite intrusions. The hydraulic conductivity of the fractured shales was measured to be in the order of 0,1 m/d. The water quality of this unit, however, is poor, with EC the being in excess of 250 mS/m, making the water unfit for human consumption.

The primary aquifer is located directly down gradient of the site, with the toe of the landfill situated on the edge of the aquifer. The aquifer comprises brown, coarse grained alluvial sand deposits. A K of 21 m/d was measured for the course sand horizons. Yields in excess of 5 L/s were recorded in the immediate vicinity of the waste facility. The ambient quality was found to be good, with the EC generally being less than 100 mS/m.

It would appear that the two groundwater systems are not in hydraulic continuity. This is based on both piezometric and water quality evidence. Based on the shallowest recorded water level measured in the alluvium, the unsaturated zone has a thickness of 2,59 m.

Discussion:

The poor quality of the groundwater of the Pietermaritzburg Formation suggests that the unit cannot be regarded as a viable aquifer. The fractured nature of the shales does indicate that, if leachate could infiltrate into the hard rock unit, it would migrate quickly with limited attenuation.

The primary aquifer, on the other hand, is potentially an aquifer of major importance. Substantial yields can be obtained while water quality is also good. The saturated thickness of the unit is probably in excess of 20 m towards the centre of the floodplain. The river provides an effective source and mechanism for recharge. The aquifer has not, however, been developed and is used on a very limited scale for irrigation and drought relief only. By the very nature of the aquifer material and its location in a major metropolitan area, the threat of contamination must be considered.

A total of 7 monitoring stations have been installed around the site, 3 of which have separate boreholes drilled into the alluvium and hard rock respectively (Figure 10). From detailed water quality logging with depth, it was found that quality stratification exists. The stratification is a direct expression of the different lithologies. Extreme caution thus has to be taken when evaluating monitored quality data.

Owing to the poor quality of water from the shale formation, limited sampling points and the lack of time series data, it is difficult to evaluate the chemistry of waters obtained from this unit. Since it appears that this water has a naturally high salinity, the impact of the waste facility on the hard rock formations is of limited concern to this study.

The quality of water from the alluvium is of more significance to this study. Contamination at the toe of the landfill is evident ie. EC of 260 mS/m. Further contamination is less apparent. A long established borehole (BSED 1) is reported to have had a 33 % increase in TDS between 1983 and 1993. Unfortunately no samples were collected between these dates and the pattern of change is not available. Thus it cannot be stated that this increase is due to contamination. The excellent quality water recorded at BSBH 2A and the relatively high EC measured at BSED 1 make it difficult to confirm that contamination has, in fact, occurred. Regularly monitored data is required for this purpose.

The fact that contamination has not been confirmed in boreholes down-gradient of the waste facility, does not suggest that the aquifer is not threatened. In the case of Site 1, contamination was detected 50 m down gradient of the waste site some 14 years after it was brought into operation. It then took 1,5 years to travel the next 100 m. This suggests that there was a lag time of some 10 to 12 years before the impacts of the site were realised. It is therefore reasonable to expect that the impact would not yet be recorded in the closest borehole, located some 200 m down-gradient of the site. If it is further considered that the area experienced severe droughts during the 1980's, then the lack of detection is even more plausible. Regular monitoring being performed by the owners of the site should, however, detect some form of contamination at BS 1 in the next few months.

It is of interest to note that significant quantities of methane have been recorded at BSBH 4. It was proposed that the fracture zone provided a route for rapid migration of the gas. However, groundwater contamination could not be confirmed.

Site suitability: The waste disposal site poses a significant threat in terms of size and nature of waste deposited. The vadose zone has limited capabilities in terms of separating the threat from the aquifer. The facility is located adjacent to a viable primary aquifer. The aquifer could play an important role as a source of water during periods of drought. The site thus has to be regarded as unsuitable for waste disposal.

Information: A report describing monitoring boreholes installed at the site was prepared by AA Loudon and Partners while the results of monitoring are presented in a report by Lombard and Associates. Documents for the permit application are currently being prepared.

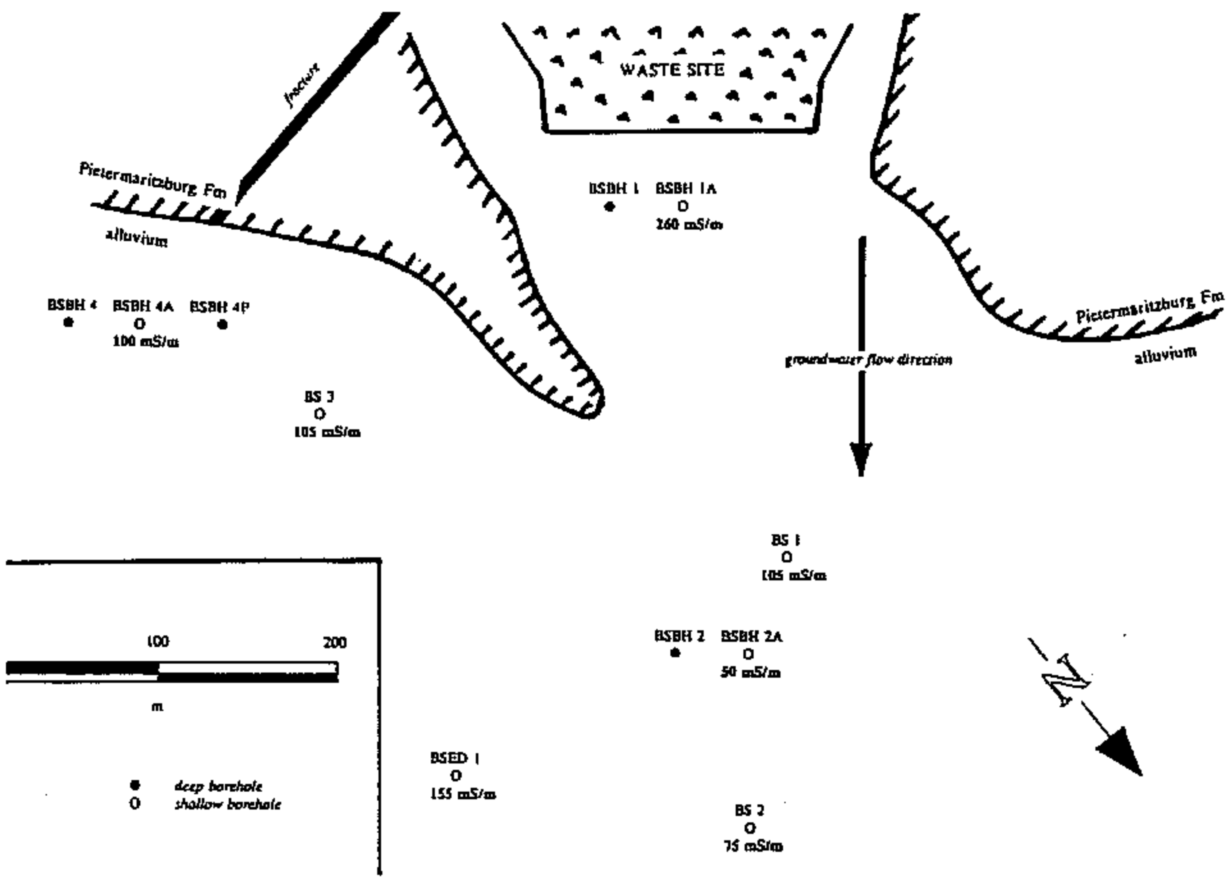


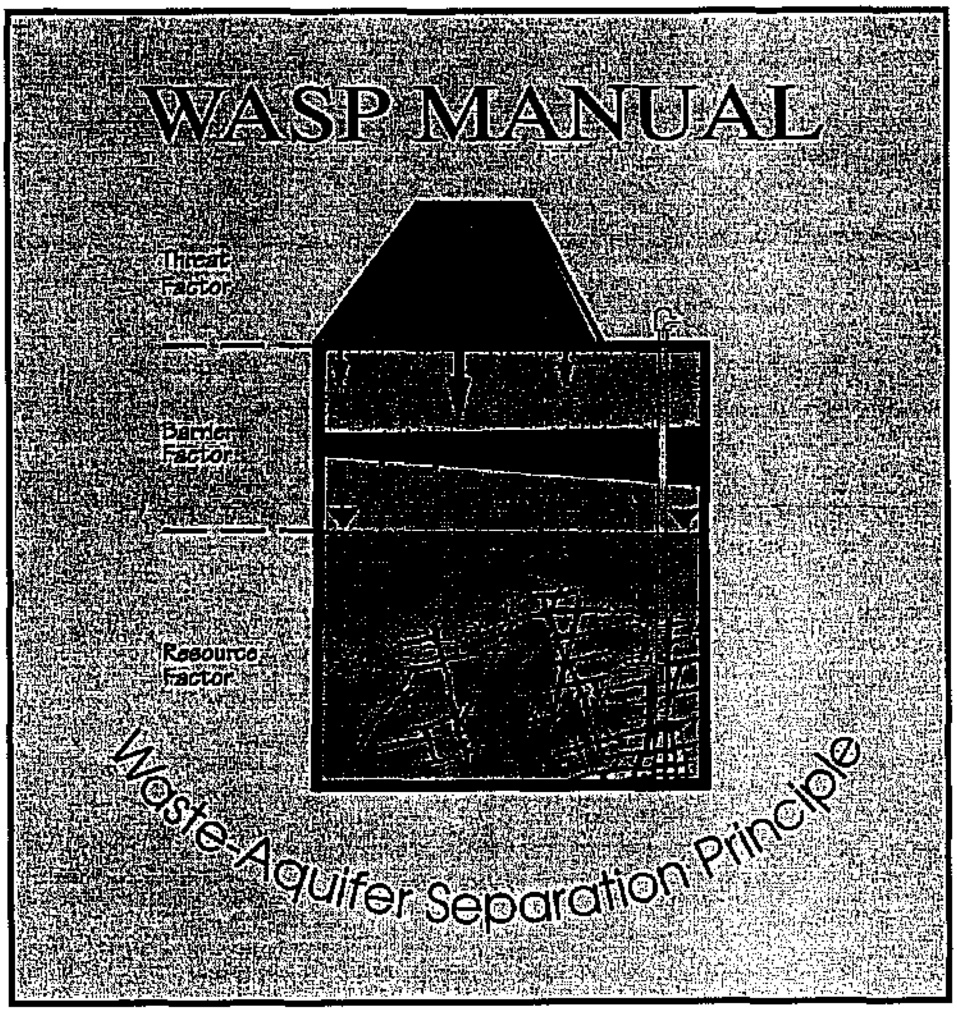
Figure 10: Electrical conductivity of waters sampled from the primary aquifer at Site 10.

APPENDIX E

WASP Manual

A systematic method for evaluating site suitability for waste disposal

based on geohydrological criteria



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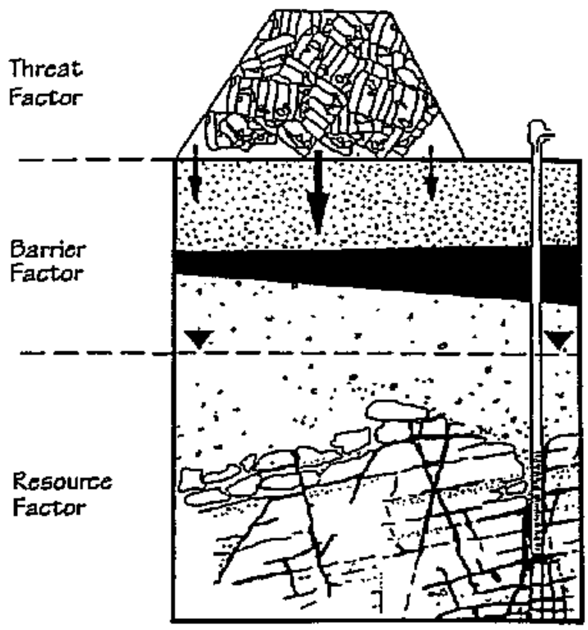
Disclaimer

PREAMBLE

The Waste - Aquifer Separation Principle, or WASP, is a tool for assessing the suitability of both existing and proposed waste facilities in terms of geohydrological criteria. The development, verification and validation of WASP are described in detail in a report by Parsons and Jolly (1994) entitled:

> *The development of a systematic method for evaluating site suitability for waste disposal based on geohydrological criteria.*

The Executive Summary of the report is included in this manual. The research was funded by the Water Research Commission of South Africa and carried out by CSIR and the Department of Water Affairs and Forestry. Copies of the research documents and the WASP software are obtainable from the Executive Director, Water Research Commission, PO Box 824, Pretoria 0001, South Africa. All users of WASP are urged to read these documents in order to gain a deeper understanding of the assumptions of the procedure as well as to be aware of the application and limitations of the tool.



WASP considers three distinct components which play a role in defining the suitability of a particular site for waste disposal:

- the *threat* posed by the waste pile
- the *barrier* between the waste pile and groundwater resources
- the groundwater *resource*.

Each factor is independently assessed before a WASP Index is calculated. The Index is then compared with a calibrated interpretation scale in order to define suitability. Coupled to each factor is a data reliability rating process. The data reliability ratings of each factor are determined and then averaged. The rating is then recorded, in parenthesis, behind the WASP Index in order to provide a measure of the degree of detail of information used to calculate the WASP Index.

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EXECUTIVE SUMMARY

PROBLEM STATEMENT

Much of South Africa experiences a semi-arid climate. Due to an increasing water demand, sedimentation in dams and a limited number of suitable dam sites, the country will soon face serious water shortages. Even though groundwater only accounts for some 13 % of the total national water supply, approximately 65 % of the area of the country relies on this water source to one degree or another. The predicted inability of surface water resources to meet future water demands and the growing cost of developing these resources suggest that groundwater resources could help meet these requirements, either in conjunction with surface resources or as a sole source. Latest estimates are that over 280 towns and smaller settlements use groundwater to one degree or another.

The disposal of waste has been shown throughout the world to be a major contributor to the degradation of aquifers. Wastes are an unavoidable by-product of all man's activities and the disposal thereof is a growing problem. Approximately 95 % of all solid waste in South Africa is disposed of by landfilling or landbuilding. It is further estimated that 1 400 solid waste disposal sites exist in South Africa. The infiltration of leachate from these sites into groundwater bodies is hence of major concern.

No formalised systems or standard approaches are used to assess the impact that waste disposal sites have, or could have, on South Africa's aquifers. This has led to variable results being obtained and inconsistent conclusions being reached in those geohydrological studies that have been undertaken at waste disposal sites. In response to this, Hall and Hanbury (1990), Jolly and Parsons (1991) and Van Tonder and Muller (1991) all proposed some form of site evaluation based on international literature. However, all were literature-based and the methods have not been tested or validated under South African geological and geohydrological conditions.

RESEARCH OBJECTIVES

The objective of the investigation was to develop and field-validate a South African-based methodology which addressed the geohydrological components of waste site selection and suitability evaluation. The developed method was to be suitable for initial site screening and planning, setting of data requirements and final site suitability determination. Further, a set of required characteristics were identified at the outset. The method was to be:

a. valid, appropriate and accurate under South African conditions;
b. systematic, physically based, objective and the results repeatable;
c. suitable for site specific investigations;
d. an easy-to-use system based on readily available geohydrological data; and
e. the methodology was to be suitable for use by the central government permitting authority, local authorities and private companies entrusted with waste disposal as well as consultants undertaking waste disposal site selection and suitability determination studies.

RESEARCH METHOD

Information concerning site evaluation techniques used elsewhere in the world were collected by means of a WATERLIT literature search, a South African study tour and a short visit to Europe. The study tours were undertaken in order that in-depth discussions could be held with people active in the field of waste management and groundwater as well as with researchers and developers of other site assessment methods. A total of 29 different site or regional assessment tools were identified and studied. The positive and appropriate features of these methods were then used to develop a conceptual method which took account of South African conditions.

Information from 106 waste site permit applications, submitted to the Department of Water Affairs and Forestry, was examined. Owing to the nature of data presented and the reliability of the data, information from only 71 of these sites could be used in the development of the method. Data pertaining to the type and volume of waste disposed of and the prevailing geological and geohydrological conditions was then collected and used in the verification of the developed method. Information from ten well-studied waste disposal sites, spread throughout South Africa, was used in the validation of the method. Additional fieldwork was required at six of these sites to obtain the required information. The data used in the development, verification and validation of the method are regarded as the best data currently available.

WASTE - AQUIFER SEPARATION PRINCIPLE

It is widely argued in the literature that most waste can be landfilled without any unacceptable detriment to the public or the environment **if the sites are carefully selected**. Further, if expensive and technically difficult groundwater contamination clean-up is to be avoided, waste facilities and aquifers must be kept apart. This separation concept is central to the method developed and led to the name **Waste - Aquifer Separation Principle**, abbreviated as **WASP**.

Three factors were identified as being important in the assessment of site suitability for waste disposal (Figure 1), namely:

- the Threat Factor
- the Barrier Factor
- the Resource Factor.

Many of the methods studied subscribed to a similar concept. One of the major differences between WASP and vulnerability mapping techniques is that vulnerability mapping does not consider the actual threat posed by the waste pile. The fact that the three elements were so distinct and easily differentiated between, in terms of both role played and actual physical boundaries, made this approach attractive.

Threat Factor

All waste disposal sites produce leachate and, as such, pose a threat to groundwater resources. The threat posed is essentially some product of the volume of leachate produced and the quality of that leachate. Both components are extremely difficult to quantify or predict with any certainty. After due consideration was given to international trends and current South African practice, it was decided that a Threat Factor score could be obtained using the designed final area of the site and the type of waste being disposed of.

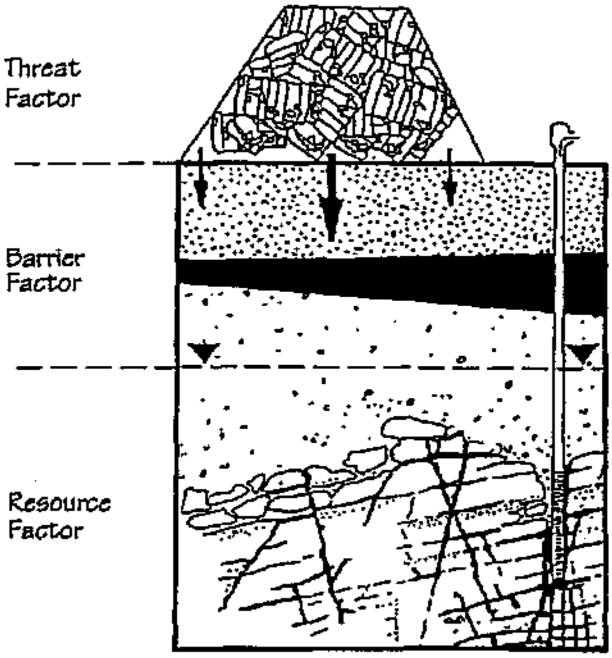

Figure 1: The three factors which impact on site suitability for waste disposal

Barrier Factor

The barrier between a waste pile and an aquifer is represented by the unsaturated zone. It is within this zone that much attenuation of leachate occurs. Important processes in leachate attenuation include chemical precipitation, adsorption, dilution, dispersion and biodegradation. Attenuation is a set of complex and often inter-related processes governed by a number of factors. The modelling of attenuation processes is hence extremely difficult. It was therefore decided that the time that leachate would take to travel from the base of the waste pile to the top of the aquifer would be used to quantify the ability of the barrier zone to separate the waste from an aquifer. Travel time is calculated using Darcy's Law. The data required for the calculation are depth to water and the hydraulic conductivity and porosity of the vadose zone. The Barrier Factor score is obtained by comparing the calculated travel time to a rating curve.

Resource Factor

The quantification of the Resource Factor proved to be most challenging. In attempting to establish the significance of a groundwater body, and then employing a single number to reflect the value of the resource, one is essentially trying to present the science of geohydrology in a short sentence. It was decided at the outset that the strategic value of a groundwater body to its user, or potential user, should be considered. This meant that a single user, such as a farmer, was given the same weighting as a large multiple user, for example a town. This required that measurable and definite parameter values be excluded from the assessment process. A questionnaire approach was shown to be the most appropriate means of assessment. Two sets of questions were compiled, the first set dealing with current usage and the second with potential usage. Points are awarded for each answer, thus enabling the quantification of the Resource Factor.

WASP Index

Once scores for all three factors have been determined, the WASP Index is computed using a nomographic solution. The obtained index can be correlated directly against a generalised interpretation, whereby sites are defined as being either highly suitable, suitable, marginal, unsuitable or highly unsuitable. The interpretation was developed and refined using information obtained from the 71 permit applications and the associated reports.

Data Reliability

In order that WASP could have a wide application, a data reliability rating was developed. All input data considered by WASP are rated in terms of their detail and reliability. A simple rating scale of 1 to 3 is used. The three data reliability levels used correspond directly to the types of investigations which may be required by current Integrated Environmental Management principles and procedures. Once all data have been rated, an average is obtained and recorded in brackets after the obtained WASP Index. The data reliability rating allows that the value and reliability of the WASP Index be readily apparent. This aspect will be particularly valuable to DWAF when considering waste site permit applications.

Flexibility

It was found during the development of WASP that not all geohydrological situations could be accommodated in the procedure. At times, one component or factor was so dominant that it over-rode the determined WASP Index. Extremely poor groundwater quality, a very slow travel time through the barrier and an extremely low groundwater potential were three commonly encountered conditions which resulted in over-ride situations. The inclusion and identification of over-ride factors was thus accommodated in WASP to account for such circumstances and hence provide flexibility in the procedure. The employment of an over-ride during site evaluation, however, can only be based on detailed and reliable data and be motivated by a suitably qualified and experience geohydrologist.

DISCUSSION

The validity of WASP was assessed by comparing the WASP Indices obtained for the 10 waste disposal sites studied in detail with observed contamination patterns. All of the obtained indices were found to be accurate assessments of the prevailing conditions. Further validation is nonetheless recommended once more data becomes available.

The integration of WASP, at all levels, into broader waste site suitability assessment procedures and approaches will provide much assistance and impetus to the prevention of contamination of South Africa's aquifers by waste disposal activities. WASP can play a valuable role in initial site screening, identification of additional data requirements and the final assessment of the a suitability for waste disposal. The incorporation of WASP into the current waste site permit application procedure is also seen as being particularly important.

Even though every effort has been made to develop an accurate and reliable tool, WASP does have some limitations. These result largely from the assumptions and simplifications used in WASP. Users of the method must thus be aware of these inherent limitations. WASP does not replace the need for appropriate data and information, nor the need for suitable geohydrological training and experience, in the assessment of site suitability for waste disposal. The procedure is merely a tool to help in the evaluation of proposed and existing sites and promotes sound decision-making. The reliability of the assessment remains a function of the data used and the expertise of the assessor.

A field manual has been prepared so that the procedure can be easily applied under field conditions. Further, software has been written which allows for the easy input of the required data and the automatic calculation of the WASP Index and the interpretation thereof.

CONCLUSIONS

Based on all the reliable waste disposal site data currently available in South Africa and the work performed during the research programme, WASP was found to be capable of providing an accurate and quantified assessment of a site's suitability for waste disposal, based on geohydrological criteria. WASP now needs to be applied to a wide range of waste and geohydrological conditions. Once applied, the performance of the procedure can then be re-assessed.

The objectives of the research project have been achieved by the development, verification and validation of the Waste-Aquifer Separation Principle, abbreviated as WASP. The method was based on 29 methods used throughout the world, but was developed to suit South African conditions. All reliable waste disposal site data currently available were used in the verification of the method while the validation of WASP was based on information from 10 well-studied facilities spread throughout the country. A data reliability rating is coupled to the WASP Index and this allows the value and reliability of the obtained Index to be readily apparent. A degree of flexibility is allowed for in the procedure in order to accommodate special or unique considerations and circumstances. WASP does not, however, replace the need for appropriate data nor the need for the assessor to be suitably qualified and experienced in geohydrology.

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GENERAL PRECAUTIONARY STATEMENT

The quality of an assessment and the accuracy of the results are directly related to the technical capability of the user and the amount and quality of available hydrogeological information. The degree of reliability achieved by anyone using WASP depends on their level of training and on the amount of information available to determine hydrogeological conditions. The application of WASP requires experience in interpreting subsurface geological and groundwater information to produce satisfactory results. It is thus required that only persons of suitable training and experience in the field of geohydrology perform the WASP assessment which will be used to make decisions regarding the suitability of a particular site for waste disposal activities.

Further, it is recognised that this method cannot be suitable for all situations. Even though every effort has been made to develop a systematic and objective methodology, which accurately defines the physical environment, the onus remains with the investigator to ensure site suitability.

WASP METHODOLOGY

THREAT FACTOR

The threat posed by the waste pile is essentially a product of the volume and quality of leachate produced by the waste pile. WASP quantifies this threat by means of the designed final area of the site and type of waste being disposed of.

STEP 1: Quantify input parameters

designed final area of site: The designed final area of the site needs to be measured in hectares.

type of waste: The type of waste being disposed of must be determined and classified according to the following groupings:

garden and building rubble
domestic waste including commercial waste
dry industrial waste and domestic waste
liquid effluent and sludge and domestic waste
hazardous waste (including medical waste)

Note that the most appropriate group must be used as well as the higher level of classification i.e. if both dry industrial waste and sewage sludge is disposed of, the waste must be classified as liquid effluent and sludge and domestic waste.

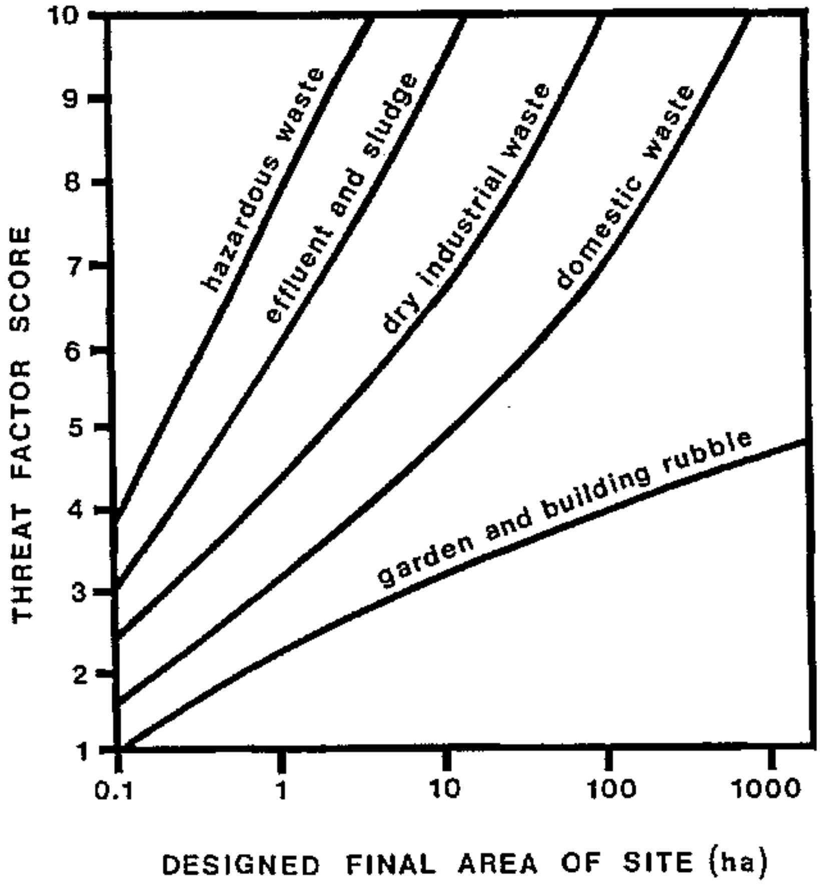
STEP 2: Determine Threat Factor score

Using the Threat Factor score nomogram, read off the Threat Factor score and record.

STEP 3: Determine data reliability rating

Using the Threat Factor score data reliability rating table, assign a point equivalent to the most appropriate level of data reliability for each component, obtain an average for the two and record ie. Level 1 data is assigned 1 point.

THREAT FACTOR SCORE NOMOGRAM



DATA RELIABILITY RATING TABLE FOR THE THREAT FACTOR

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Size of site	Certain - based on site field measurement or approved final site plan.	Based on aerial photograph or map measurements and estimations.	Uncertain - based on estimations.
Waste type	Certain - based on observed and monitored waste deposition.	Based on extrapolated information from similar situations.	Uncertain - based on estimations.

BARRIER FACTOR

The time that leachate would take to travel from the base of the waste pile to the top of the aquifer is regarded as a measure of the ability of the unsaturated zone to attenuate the leachate and hence separate the waste from any groundwater resources. Travel time is calculated using Darcy's Law and the required input parameters are the thickness of the unsaturated zone, the hydraulic conductivity of the zone and the porosity of the barrier material. The hydraulic gradient is assumed to approximate unity and can be ignored.

STEP 1: Quantify input parameters

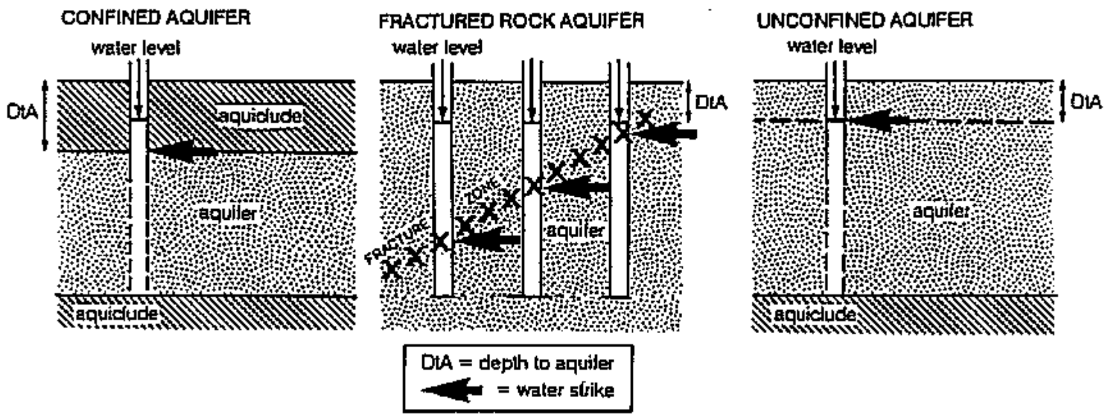
thickness of barrier zone: The top of an aquifer is defined by the static water table (or piezometric surface); the thickness of the barrier zone is hence measured in metres from the base of the waste pile to the water table. See conditions where the thickness may be measured otherwise (next page).

hydraulic conductivity: The hydraulic conductivity, recorded in m/day, must be provided. For the purpose of guidance, some typical ranges of values for different lithologies are presented in a table on the next page. *The highest measured hydraulic conductivity must be used.*

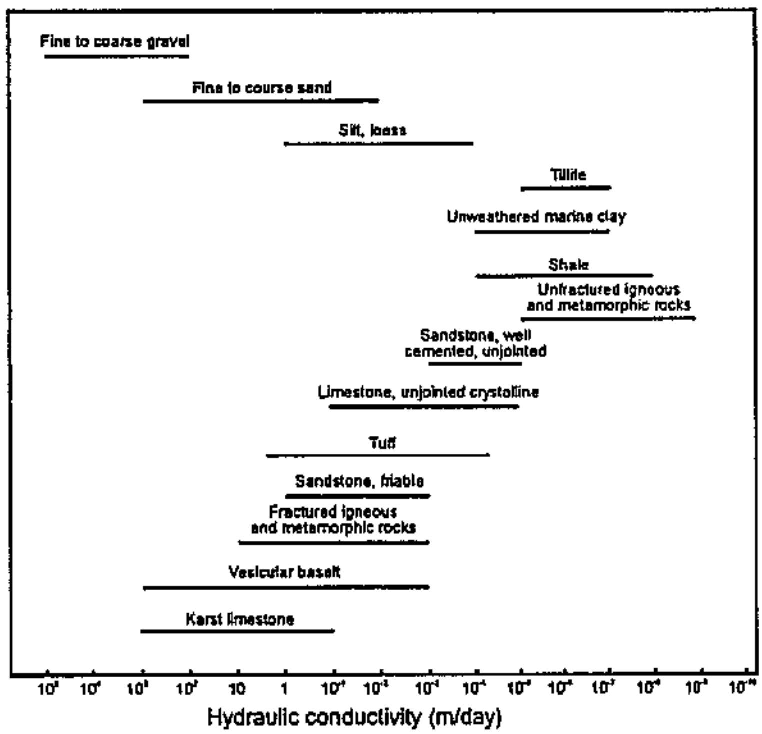
porosity: The porosity of the vadose zone must be assigned. Some typical ranges of porosity for different lithologies are presented in a table on the next page. It must be borne in mind that the porosity of fractured rocks may range between 1 % and 0.1 %. Unless more detailed information are available, a porosity of 20 % is usually assumed.

Note that if more than one distinct horizon is present in the barrier zone, the required input parameters must be used to determine the individual travel time through each horizon. A total travel time is calculated by adding the travel times for each horizon.

CONDITIONS UNDER WHICH THE TOP OF AN AQUIFER IS NOT DEFINED BY STATIC WATER OR PIEZOMETRIC LEVEL



TYPICAL K VALUES FOR DIFFERENT LITHOLOGIES



(After Driscoll, 1986)

TYPICAL RANGES OF POROSITY FOR DIFFERENT LITHOLOGIES

Unconsolidated Sediments	η (%)	Consolidated Rocks	η (%)
Clay	45–55	Sandstone	5–30
Silt	35–50	Limestone/dolomite (original & secondary porosity	1–20
Sand	25–40	Shale	0–10
Gravel	25–40	Fractured crystalline rock	0–10
Sand & gravel mixes	10–35	Vesicular basalt	10–50
Glacial till	10–25	Dense, solid rock	< 1

(Driscoll, 1986)

STEP 2: Calculate the travel time

Using the travel time formula based on Darcy's Law, calculate the individual travel time for each horizon and add to obtain a total travel time in days.

TRAVEL TIME FORMULA

$$Tt = \frac{d}{[K / (n/100)]}$$

Tt	travel time (days)
d	thickness of barrier zone (m)
K	hydraulic conductivity (m/day)
n	porosity (%)

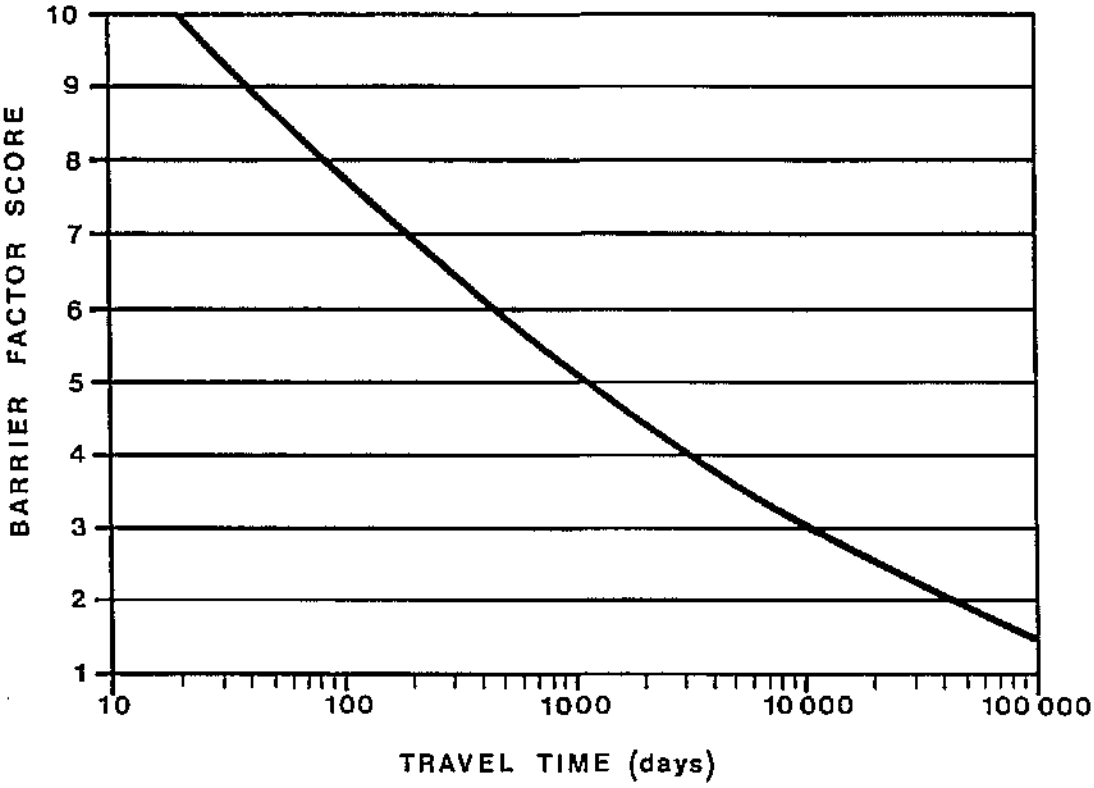
STEP 3: Determine Barrier Factor score

Using the Barrier Factor score nomogram, read off the Barrier Factor Score and record.

STEP 4: Determine data reliability rating

Using the Barrier Factor score data reliability rating table, assign a point for each component equivalent to the most appropriate level of data reliability, obtain an average for the Factor and record i.e. Level 1 data is assigned 1 point.

BARRIER FACTOR SCORE NOMOGRAM



DATA RELIABILITY RATING TABLE FOR THE BARRIER FACTOR

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Thickness	Certain - based on site specific measured depth to water, drilling data and geohydrological borehole log.	Based on measured depth to water, extrapolated information from similar areas.	Uncertain - based on estimation from national or regional maps, guesstimation.
K	Certain - based on site specific *in situ* tests - aquifer tests, borehole percolation tests, double ring infiltrometer tests etc.	Based on laboratory analyses, surface infiltrometer tests, extrapolated information from similar lithologies, standard tables.	Uncertain - based on standard tables, guesstimation.
Porosity	Certain - based on field analyses and laboratory analyses.	Based on extrapolation from similar lithologies, standard tables.	Uncertain - based on standard tables, guesstimation.

RESOURCE FACTOR

The strategic value of a groundwater resource to a ***user***, or ***potential users*** must be based on fitness-for-use in terms of quantity and quality, forming the basis for the quantification of the Resource Factor. The resource is considered in terms of groundwater usage and groundwater potential. A user can range from a single farmer using an aquifer for domestic and agricultural purposes, to a town or city, which does or could use an aquifer as a sole water source or in conjunction with other water sources. All users are treated as having equal weight.

STEP 1: Quantify input parameters

groundwater usage: Answer the groundwater usage questions presented in the Resource questionnaire. Remember to answer the questions in terms of the user of the resource.

For each yes, do not know or maybe answer, award 2 points.
Assign points for the percentage of groundwater used, using the groundwater usage bar scale.
Add the points and record (minimum of 1 and maximum of 10).

groundwater potential: Answer the groundwater potential questions presented in the Resource questionnaire. Remember to answer the questions in terms of potential users of the resource.

For each yes, do not know or maybe answer, award 2 points.
Add the points and record (minimum of 0 and maximum of 10).

STEP 2: Determine Resource Factor score

Add the groundwater usage and groundwater potential points (minimum of 1 and maximum of 20) and, using the Resource Factor bar scale, determine the Resource Factor score and record.

STEP 3: Determine data reliability rating

Using the Resource Factor score data reliability rating table, assign a point, for each set of questions, equivalent to the most appropriate level of data reliability, obtain an average and record i.e. Level 1 data is assigned 1 point.

RESOURCE QUESTIONNAIRE

Groundwater Usage	Groundwater Potential
a. Is groundwater used to meet present water requirements in the area immediately adjacent to the site? b. Is groundwater used within 2 km of the waste pile? c. Is the waste pile located up-gradient of the groundwater users? d. What percentage of water demand is met from groundwater resources?	a. Does the geology of the area portray any features typically associated with usable aquifers? b. Is the long-term safe yield of the aquifer sufficient to fully or partially meet local demand? c. Can the aquifer be used for drought relief purposes or be used locally for reticulation management? d. Is the groundwater quality such that it is fit for use by the potential user? e. Is the waste site the only contamination risk which could threaten aquifer potential?

Note that the 2 km standard set here is merely a guide. In the case of small sites, a smaller radius could be used while at large hazardous facilities, a radius of 5 km may be appropriate. The professional judgement of the geohydrologist performing the assessment must be used.

GROUNDWATER USAGE BAR SCALE

Percentage of water demand met from groundwater resources

0 25 50 75 100

1 2 3 4

Groundwater Usage component score

RESOURCE FACTOR BAR SCALE

Groundwater Usage and Groundwater Potential components combined score

0 5 10 15 20

0 1 2 3 4 5 6 7 8 9 10

Resource Factor score

DATA RELIABILITY RATING TABLE FOR RESOURCE FACTOR SCORE

DATA RELIABILITY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3
Groundwater usage	Certain - based on full hydrocensus, records and reports.	Based on partial hydrocensus and discussions with local residents, driller or geohydrologist.	Uncertain - based on estimations.
Groundwater potential	Certain - based on full geohydrological investigation and detailed study.	Based on extrapolation of information from other areas, discussions with local geohydrologists familiar with the area etc.	Uncertain - based on estimations, interpretation of regional and national geological and geohydrological maps.

SPECIAL PROCEDURES

It is recognised that WASP cannot accommodate all geohydrological situations. A flexible approach is required for unique situations. Two mechanisms are used to facilitate flexibility in WASP:

Over-ride factors: Over-ride factors are defined as those factors of such importance that they can be used singularly to determine the suitability of a site for waste disposal i.e. they over-ride the determined WASP Index. Extremely poor groundwater quality, an extremely slow travel time through the barrier zone and close proximity to water supply boreholes are three common examples of over-ride factors.

Detailed specific investigation: At times, unique geohydrological conditions may be encountered which are not accommodated in WASP. These situations may require more detailed investigation. For example, two different geological units may be located next to one another. The one unit may be very suitable for waste disposal activities while the other has been developed for water supply purposes. A detailed investigation may be required to prove that the two are not in hydraulic continuity and that waste disposal activities may hence take place on the appropriate unit.

It is not possible to provide guidelines as to when a particular consideration becomes an over-ride, or when a unique situation exists which requires more detailed study. The professional judgement of the geohydrologist performing the assessment must be relied on to identify such factors and circumstances and motivate why a special procedure may be adopted. However, such a motivation may only be based on data with a Level 1 data reliability rating i.e. measured and quantified field data which are sufficient to conclusively prove the validity of the motivation.

WASP INDEX DETERMINATION

The suitability of a particular site for waste disposal is determined by obtaining and interpreting a WASP Index. The WASP Index is calculated using the WASP Index nomogram which requires the Three Factor scores as input parameters.

STEP 1: Calculate WASP Index

Using the WASP Index nomogram, determine the Index using the Resource Factor score, the Barrier Factor score and the Threat Factor score. Record the Index.

STEP 2: Calculate the data reliability rating

Using the data reliability rating obtained for each factor, obtain an average and record the final rating in brackets behind the Index.

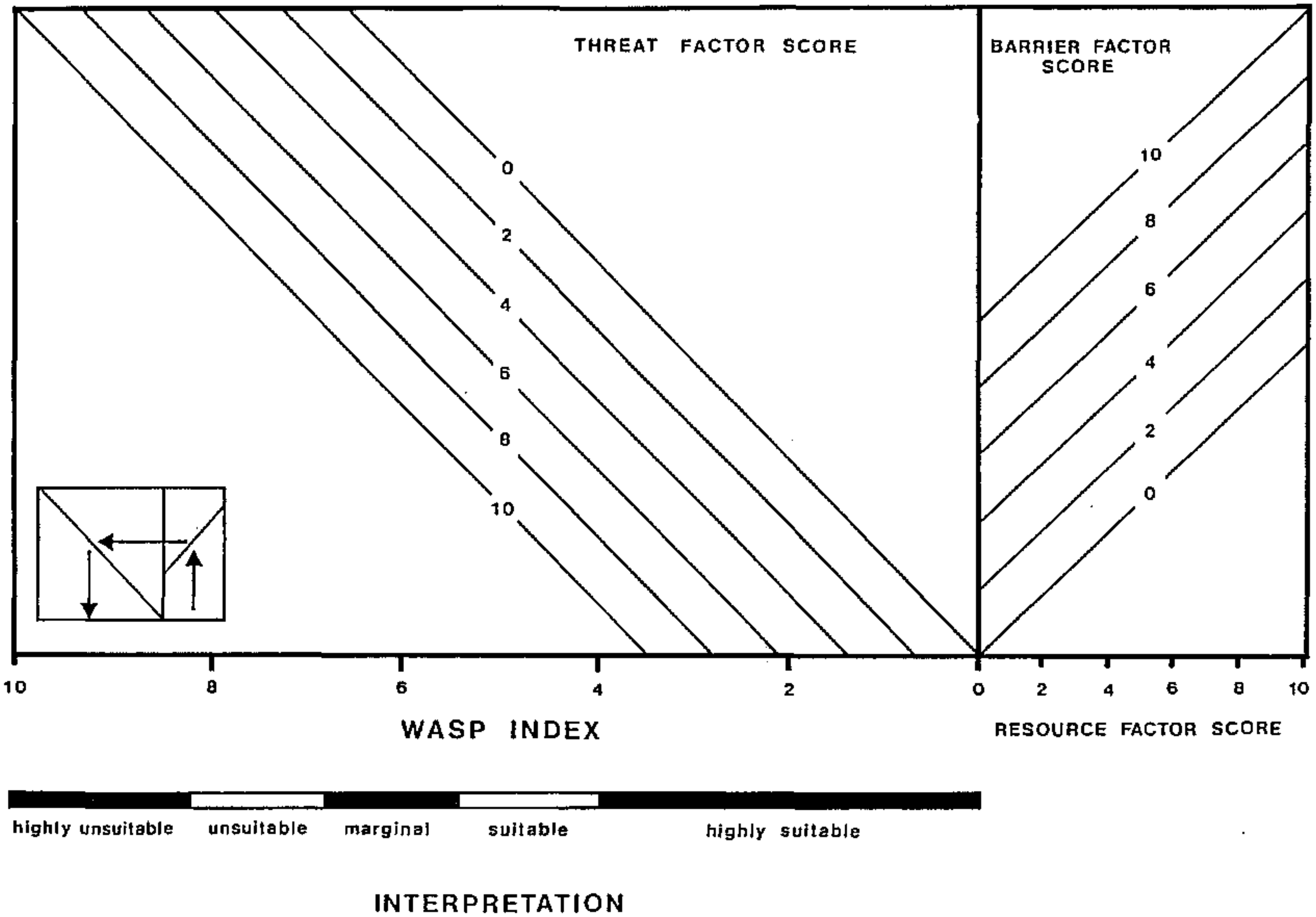
STEP 3: Assess site suitability

Compare the obtained Index to the generalised interpretation bar scale in the WASP Index nomogram. Note that this interpretation can only be considered as a guide to the interpretation.

A data reliability rating of less than 2 indicates that reasonably detailed and quantified data were used in the WASP assessment. A rating of greater than 2 demonstrates that much of the assessment was based on limited data and estimations. Such a rating would typically only be acceptable for planning applications, or ranking of possible sites in order to identify the most feasible site(s) which warrant further investigation.

An example of an assessment is presented in Appendix A, together with spare data sheets.

WASP INDEX NOMOGRAM



WASP SOFTWARE

Software has been developed to facilitate the easy and rapid application of the procedure. The software operating manual is presented as Appendix B of this field manual.

APPENDIX A

Example of a WASP Assessment

WASP Data Sheets

WASP DATA SHEET

NAME OF SITE: Reading Site OWNER: Municipality

TOWN: Barrassville LOCATION: 5km north of town

SPECIAL FEATURES: Runoff drains, leachate collection trenches

COMMENTS: Only waste facility in town

NAME OF ASSESSOR: John Smith DATE: 2 May 1994

THREAT FACTOR

designed final area (ha) 15 ha — data reliability rating: 1

type of waste: domestic — data reliability rating: 1

Threat Factor score: 5,4 — data reliability rating: 1,0

BARRIER FACTOR

Layer	d (m)	K (m/day)	n (%)	Tt (days)
Layer 1	2,3	1,3	20	0,35
Layer 2	1,6	0,0006	30	800
Layer 3	1,7	0,03	20	11,3
Layer 4				
Layer 5				
			Total Tt	812

Barrier Factor score: 5,3 — data reliability rating: 1,7

RESOURCE FACTOR

groundwater usage component score: 8 — data reliability rating: 1

groundwater potential component score: 10 — data reliability rating: 2

combined groundwater score: 18

Resource Factor score: 9,3 — data reliability rating: 1,5

WASP INDEX

WASP Index: 6,6 — *data reliability rating:* 1,4

Site suitability interpretation: marginal

WASP DATA SHEET

NAME OF SITE: OWNER:

TOWN: LOCATION:

SPECIAL FEATURES:

COMMENTS:

NAME OF ASSESSOR: DATE:

THREAT FACTOR

designed final area (ha) data reliability rating:

type of waste: data reliability rating:

Threat Factor score: data reliability rating:

BARRIER FACTOR

Layer	d (m)	K (m/day)	n (%)	Tt (days)
Layer 1 Layer 2 Layer 3 Layer 4 Layer 5			Total Tt	

Barrier Factor score: data reliability rating:

RESOURCE FACTOR

groundwater usage component score: data reliability rating:

groundwater potential component score: data reliability rating:

combined groundwater score:

Resource Factor score: data reliability rating:

WASP INDEX

WASP Index: data reliability rating:

Site suitability interpretation:

WASP DATA SHEET

NAME OF SITE: OWNER:

TOWN: LOCATION:

SPECIAL FEATURES:

COMMENTS:

NAME OF ASSESSOR: DATE:

THREAT FACTOR

designed final area (ha) data reliability rating:

type of waste: data reliability rating:

Threat Factor score: data reliability rating:

BARRIER FACTOR

Layer	d (m)	K (m/day)	n (%)	Tt (days)
Layer 1				
Layer 2				
Layer 3				
Layer 4				
Layer 5				
			Total Tt	

Barrier Factor score: data reliability rating:

RESOURCE FACTOR

groundwater usage component score: data reliability rating:

groundwater potential component score: data reliability rating:

combined groundwater score:

Resource Factor score: data reliability rating:

WASP INDEX

WASP Index: *data reliability rating:*

Site suitability interpretation:

WASP DATA SHEET

NAME OF SITE: OWNER:

TOWN: LOCATION:

SPECIAL FEATURES:

COMMENTS:

NAME OF ASSESSOR: DATE:

THREAT FACTOR

designed final area (ha) data reliability rating:

type of waste: data reliability rating:

Threat Factor score: **data reliability rating:**

BARRIER FACTOR

Layer	d (m)	K (m/day)	n (%)	Tt (days)
Layer 1 Layer 2 Layer 3 Layer 4 Layer 5			Total Tt	

Barrier Factor score: **data reliability rating:**

RESOURCE FACTOR

groundwater usage component score: data reliability rating:

groundwater potential component score: data reliability rating:

combined groundwater score:

Resource Factor score: data reliability rating:

WASP INDEX

WASP Index: *data reliability rating:*

Site suitability interpretation:

WASP DATA SHEET

NAME OF SITE: OWNER:

TOWN: LOCATION:

SPECIAL FEATURES:

COMMENTS:

NAME OF ASSESSOR: DATE:

THREAT FACTOR

designed final area (ha) data reliability rating:

type of waste: data reliability rating:

Threat Factor score: **data reliability rating:**

BARRIER FACTOR

Layer	d (m)	K (m/day)	n (%)	Tt (days)
Layer 1				
Layer 2				
Layer 3				
Layer 4				
Layer 5				
			Total Tt	

Barrier Factor score: **data reliability rating:**

RESOURCE FACTOR

groundwater usage component score: data reliability rating:

groundwater potential component score: data reliability rating:

combined groundwater score:

Resource Factor score: **data reliability rating:**

WASP INDEX

WASP Index: *data reliability rating:*

Site suitability interpretation:

APPENDIX B

WASP Software Manual

WASP SOFTWARE MANUAL

> The following minimum hardware is required to run the WASP software:
>
> - a 386 computer
> - a colour monitor
> - VGA graphic capability
> - at least DOS 3.1

1. INITIATION

The software can operate either from the A drive or can be copied from the floppy onto the C drive. The programme is initiated by entering the executable command <*WASP*>. This command will initiate the programme and produce the first screen with the WASP logo and title. Keying <*Enter*> will move on from the first screen to the remainder of the programme. The first three screens provide some background to WASP. To move from one screen to the next key <*Enter*>. Should you wish to bypass the background information screens, key <*F5*>.

2. PROGRAMME OPTIONS

After the background information has been presented, the user has the following options:

a. *Open new WASP profile*
b. *Retrieve WASP profile*
c. *Print WASP profile*

To select the option wanted, either move the highlight to the option required and press <*Enter*> or type the letter <*N*>, <*R*>, or <*P*> to initiate the next step.

2.1. Opening a New WASP Profile

Once you have keyed <*N*> or entered the highlight on *Open WASP profile*, you will be asked to input a profile name. This name must be limited to eight characters. Once you have entered the site name, press <*Enter*> to bring up a new screen where the following site information can be entered:

a. site name and site owner
b. town and location
c. date
d. evaluator
e. features and comments.

For each one of the above inputs, the <*F1*> key provides a help screen in which it is explained what information must be entered. For example, if one types <*F1*> under *site name*, you will be informed *Type in the name of the waste site*. To exit from the *F1* mode, merely press the <*Esc*> key.

At any stage in the WASP programme, one can move from one input box to the next using the <*Tab*> key. <*Tab*> moves you one box forward, while <*Shift Tab*> moves you one box backwards. Once you have entered all the required information, follow the instructions as at the base of the screen, i.e. *F5 to go to next stage*.

2.2. Retrieving a WASP Profile

To retrieve an existing WASP profile, enter <*R*> or move the highlight to *Retrieve WASP profile* and key <*Enter*>. A new screen will appear containing a list of all the existing files which have previously been saved. Only nine files can be shown on the screen at any one time, but by using the up and down arrows, one can scroll through the complete list.

To select the file which you would like to retrieve, use the up or down arrows to highlight the file required and key <*Enter*>. The *site information* screen will then appear. Should you wish to edit any of the data presented on this screen, move to the required box and make the necessary changes. When the necessary edits have been made, follow the command at the bottom of the screen, i.e. *F5 to go to the next stage*.

2.3. Printing a WASP Profile

To print a WASP profile, type <*P*> or move the highlight to *Print a WASP profile* and press <*Enter*>. A file list will appear and by using the up and down arrows, one can highlight the file one wishes to have a printout of. Once the file has been selected, key <*Enter*>. The WASP profile will then be sent to the printer and a hardcopy produced. Wait until the option screen is re-displayed.

NOTE: Before printing, make certain that your printer is in graphics mode. To do this, run the DOS programme <GRAPHICS> from the DOS prompt *before* starting the WASP programme.

3. ENTERING DATA

3.1. Stage 1: Threat Factor Score

Four data inputs are required to calculate the Threat Factor score:

a. the size of the site and the reliability of the data, and
b. the type of waste site and the reliability of the data.

The <*F1*> help key can, at any stage, be used to explain what data input is required. To exit from the help screen, key <*Esc*>.

3.1.1. Size of the Site

The size of the site is defined as the designed final site area, measured in hectares. Once this data have been entered, the programme automatically moves on to the data reliability box for that input. Selected the applicable highlighted score of 1, 2 or 3 and key <*Enter*>.

3.1.2. Waste Type

The programme automatically presents a list of the waste categories. Select the applicable type by moving the highlight to the appropriate type using the arrow keys and keying <*Enter*> or by entering the corresponding number from 1 to 5. Once the waste type has been entered, the programme automatically moves on to the data reliability box for that input. Selected the applicable highlighted score of 1, 2 or 3 and key <*Enter*>.

3.1.3. Threat Factor Score Calculation

Once the data have been entered, the software automatically uses the nomogram to calculate the Threat Factor score. The calculated Threat Factor score is shown graphically on the nomogram and is also recorded to the right of the nomogram together with the data reliability rating.

Alterations to the data entered can be made by moving between the different input boxes, using the <*Tab*> and <*Shift Tab*> keys, modifying the data and while still in the box being altered, keying <*F2*>. A re-calculation of the Threat Factor score is then immediately performed and the score updated. If <*F2*> is not keyed, the changes will not be recorded.

Once the Threat Factor score has been calculated, one can proceed to the next stage of the WASP evaluation by keying <*F5*>.

3.2 Stage 2: Barrier Factor Score

The data inputs required to calculate the Barrier Factor score are:

a. the thickness of each geohydrologically distinct unit or layer in the unsaturated zone;
b. the hydraulic conductivity of each unit;
c. the porosity of each unit; and

d. the data reliability for each of the data inputs.

A travel time is calculated for each layer and the total travel time is used to quantify the Barrier Factor score by means of a nomogram. A brief explanation of the basis of this component is given by entering *<F1>* when the Barrier Factor score screen is first displayed.

3.2.1. Thickness

The thickness of the barrier zone is usually defined as the depth to water, measured in m. The thickness of each individual unit or layer needs to be determined from soil profiles or borehole logs. Once the thickness has been entered, the highlight moves directly to the data reliability box for the preceding data input.

3.2.2. Hydraulic Conductivity

The hydraulic conductivity and the associated data reliability of each layer is required. Hydraulic conductivity is expressed as m/day. As a first approximation, a list of some typical values for different lithologies is presented by keying *<F1>*. Should the data from the help screen be used, a data reliability of 3 *must* be recorded.

The programme only accepts values ranging between 99 m/day and 0.00000001 m/day.

3.3.3. Porosity

The porosity and the associated data reliability of each layer are required. Porosity is expressed as a percentage. As a first approximation, a list of some typical values for different lithologies is presented by keying *<F1>*. Should the data from the help screen be used, a data reliability of 3 *must* be recorded. Attention must be paid to the value used when dealing with fractured environments, as the porosity can be an order of magnitude less than in the case of porous media.

3.3.4. Barrier Factor Score Calculation

As the data are being entered, the programme automatically calculates the travel time through each unit. The total travel time for the various layers is the summation of the travel time for each of the layers and is shown at the bottom of the table. Further, as the data for each horizon are entered, the calculated Barrier Factor score will immediately register on the nomogram. If the total travel time is calculated at less than 10 days, the Barrier Factor score is automatically considered to be 10.

NOTE: Those fields not required in the input table are left with default 0 values i.e. if only one layer is present, the remaining input boxes for layers 2 to 5 stay as default 0 values.

Once the information for all the layers have been entered, the final barrier score will be shown graphically on the nomogram. The Barrier Factor score is also recorded to the right of the nomogram together with the Factor score data reliability rating.

Alterations to the data entered can be made by moving between the different input boxes, using the *<Tab>* and *<Shift Tab>* keys, modifying the data and while still in the box being altered, keying <*F2*>.

Once the Barrier Factor score has been calculated, one can proceed to the next stage of the WASP evaluation by keying <*F5*>.

3.3. Stage 3: Resource Factor Score

The Resource Factor is assessed by answering a set of questions relating to:

a. groundwater usage, and
b. groundwater potential.

To proceed with the determination of the Resource Factor score, type either <*U*> or <*P*>.

3.3.1. Groundwater Usage

The input required in order to answer the questions asked are either <*No*>, <*Yes*>, <*Maybe*>, or <*Don't know*>. Either type the letters <*N*>, <*Y*>, <*M*> or <*D*> or highlight the appropriate answer using the arrow keys and key <*Enter*>. The answer to each question must also be accompanied by the level of data reliability for that answer.

As the data are entered, the score and data reliability for Groundwater Usage is immediately calculated by the programme and shown at the bottom of the screen. Be sure to answer all questions.

Once the data reliability is entered for the final question, the programme will immediately return to the main Resource Factor score screen and allow you to then select the Groundwater Potential questions by entering <*P*>.

3.3.2. Groundwater Potential

The procedure for entry of the answers to the questions for Groundwater Potential is the same as that for Groundwater Usage. Once the final question is answered, the programme returns to the main Resource Factor screen.

3.3.3. Resource Factor Score

Once the final question under Groundwater Potential has been answered and its data reliability rating has been entered, the Resource Factor score is automatically calculated by the programme. The score, together with the data reliability rating, is recorded at the bottom right hand side of the screen. Be sure that each individual question has been properly answered.

All the data required for the WASP Index calculation have now been entered. Proceed to the index calculation by keying <*F5*>.

4. CALCULATION OF WASP INDEX

As the WASP Index nomogram appears on the screen, the programme initiates the WASP

Index calculation. This is indicated by the movement of the red line on the monogram.

The final WASP Index is recorded both graphically and beneath the nomogram. The suitability of the site, based on geohydrological criteria, is also displayed, as is the WASP Index data reliability rating.

A help screen <*F1*> exists to explain special procedures or important over-ride factors which may need to be considered in the final assessment of the site suitability. Key <*Esc*> to exit from the help mode.

Key <*F5*> to return to the start of the data input (Stage 1) for that waste site, should you wish to make some alterations.

Key <*Enter*> to save data and exit.

5. SAVE PROFILE AND EXIT

Data from a site profile can be saved at anytime by keying <*Esc*>. The programme will then ask if one wants to save the current WASP profile. Having entered either <*Y*> and a profile name or <*N*>, the programme returns to the options screen. At this stage one can either print out the WASP profile, retrieve another existing WASP profile, open a new profile or exit from the programme by keying <*Esc*>.

To exit from the programme at anytime, key <*Esc*> until the DOS prompt appears on the screen.

IMPORTANT KEYS

<*F1*>	help	<*Esc*>	exit help screen
<*F2*>	calculate	<*Esc*>	save WASP profile
<*F5*>	go to next stage	<*Esc*>	exit programme
<*Enter*>	select highlight	<*Tab*>	move one box forward
		<*Shift Tab*>	move one box back