Risk based decision tool for managing and protecting groundwater resources

by

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THESIS

Submitted in the fulfilment of the requirements for the degree of Doctor of Philosophy in the Faculty of Natural Science and Agriculture, Department of Geohydrology, University of the Free State, Bloemfontein

IGS

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November 2001

If a man will begin with certainties, he will end in doubts; but if he will be content to begin with doubts, he will end in certainties - Francis Bacon.

Acknowledgements

I hereby wish to express my sincere thanks to a large number of people who have inspired me to complete this thesis:

- I gratefully express appreciation to the Director, Professor F.D.I. Hodgson and all the lecturers at the Institute for Groundwater Studies for sharing their knowledge and expertise.
- To my promoter Gerrit van Tonder, thank you for your guidance, advice and support throughout the project.
- The research discussed in this thesis emanates from a project funded by the Water Research Commission entitled: "Decision Tool for establishing a Strategy for protecting groundwater resources: Data requirements, Assessment and Pollution Risk". The financing of the project by the Water Research Commission is gratefully acknowledged.
- There are many experts in groundwater and risk assessments that made a large contribution to ensuring that the decision tool is realistic, they are Gerrit van Tonder, Ricky Murray, Brent Usher, Bettina Genthe, Christine Colvin and Dave Le Maitre. Thank you for all your advice and hours spent checking various components of the decision tool.
- A special word of thanks to my parents for all your support and for the numerous opportunities you have given me to further my education.
- To the rest of my family and my in-laws, I am grateful for your love, encouragement and understanding throughout the project.
- To my dear husband, thank you for all your love, encouragement and endless patients. Thank you for all the hours you spent helping me program the decision tool.
- Last but not least my Heavenly Father, without Him at my side I would not have been able to complete this thesis.

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LATIN SYMBOLS

a	Distance between production borehole and boundary	L
a	Filter parameter	
b	Distance between production borehole and boundary	L
b	Extent of the flow domain	L
b	Thickness of the aquifer	L
d	Length of the tested section in the borehole	L
dh/dl	Horizontal hydraulic gradient	
dh/dt	Change in hydraulic head with time	L/T
e_u	Value of observation at time u	L
h	Hydraulic head	L
i	Number of observations	
i	= dh/dl	
n	Non-integer flow dimension	
n_e	Effective or kinematic porosity	
m	Counter/index	
q	Part of monthly flow attributed to high flow	L^3/T
r	Distance along the flow path between the abstraction and observation borehole, or between the injection and abstraction borehole	L
r	Distance between two boreholes	L
r	Parameter characterized by dose-response curves	
r	Radius of borehole	L
r	Protection length of borehole/aquatic ecosystem	L
r	Radiation risk coefficient	
r_e	Radius of influence	L
r_{TOT}	Time of travel radius	L
s	Drawdown in borehole at distance = r and time = t	L
$s_{Boundary}/s_b$	Drawdown as result of boundary	L
s_{well}	Drawdown in borehole	L
s_c	Drawdown in borehole under investigation as a result of the closest abstraction borehole	L
s_i	Drawdown in borehole under investigation as a result of abstraction borehole i	L
s_{total}	Drawdown in borehole under investigation as a results of its abstraction rate, boundaries and other abstracting boreholes	L
t	Time since starting the test	T
t_d	Time elapsed from the injection of tracer until the centre of mass of the tracer is recovered	T
t_p	Time elapsed from start of pumping until the centre of mass of the tracer is recovered	T
u	Time	
u	Defined as $r^2S_{sf} / 4K_ft$	
v	Groundwater velocity	L/T
v_f	Groundwater velocity under forced flow conditions	L/T
x	Cartisian coordinate	L
x	Input variable	
y	Cartisian coordinate	L
y	Output variable	
A	Area of the core disc	L^2
A	Cross sectional area normal to the direction of flow	L^2
A	Area over which pollutant is being injected	L^2
A	Ecological protection area	L^2
A	Fuzzy set	
ADD	Average daily dose	M/ MT
B	Conclusion of rule	
B	Benefits of alternative	Rands

BW	Body weight	M
C	Concentration of the tracer/pollutant	M/L^3
C	Costs of alternative	Rands
C_0	Initial concentration	M/L^3
C^A	Concentration in compartment A	M/L^3
C^B	Concentration in compartment B	M/L^3
Cl_{gw}	Harmonic mean of chloride content in boreholes	M/ L^3
Cl_p	Chloride concentration in rainfall	M/ L^3
Cl_w	Chloride concentration in soil water below active root zone in unsaturated zone/groundwater	M/ L^3
CPF	Cancer potency factor	MT^{-M}
D	Dry chloride deposition	$M/ L^2/T$
D	Fractal dimension	
D	Aquifer thickness	L
D_L	Longitudinal dispersion coefficient (= α_L v)	L^2/T
D_T	Transverse dispersion coefficient (= α_T v)	L^2/T
$D_{t2\rightarrow t1}$	Effective diffusion coefficient measured between time t_1 and t_2	L^2/T
D	Dispersion coefficient	L^2/T
D	Matrix diffusion coefficient	L^2/T
Dose	Total dose	M
DR	Drainage resistance	
ED	Exposure duration	T
EOP	End of pumping test	
F	Favourable	
H	Hurst exponent	
I	Input	
I	Groundwater inflow	L^3/T
IR	Intake rate	L^3/T
IFR	Inflow stream requirement	L^3/T
K	Horizontal hydraulic conductivity	
K_0	Modified Bessel function of the second kind and zero order	
K_f	Hydraulic conductivity of the fracture system	L/T
KD	Transmissivity	L^2/T
L	Migration distance	L
L	Thickness of the core disc	L
L	Length of flow path	L
LADD	Lifetime average daily dose	M/MT
M	Injection rate of pollutant	M/L
M_N	Average e_u over N periods	
N	Defined as 1-n/2	
N	Exposure (number of microbiological organisms)	
O	Groundwater outflow	L^3/T
P	Mean annual precipitation	L/T
P_f	Probability of failure	
Q	Rate at which contaminant is being injected	L^3/T
Q	Pumping rate during recovery of a tracer	L^3/T
Q	Pumping rate of the borehole	L^3/T
Q	Monthly flow in surface water body	L^3/T
QB	Part of monthly flow which can be attributed to base flow	L^3/T
R	Range of X	
R	Recharge	L/T
R	Risk	
R_fD	Reference dose	M/MT
S	Specific yield	
S	Storage coefficient of the aquifer	
S	Standard deviation	
S_{sf}	Specific storage of the fracture system	1/L
SF	Safety factor	
T	Time horizon	
T	Transmissivity	L^2/T

TD	Total chloride deposition at surface	$M/L^2/T$
U	Unfavourable	
V^B	Volume of solution in compartment B	L^3
W	Length of ecological protection area perpendicular to groundwater flow	L
W	Truth values	
W(u)	Well function	
$X_{t,N}$	Cumulative deviation of N periods	

GREEK SYMBOLS

α	Parameter characterized by dose-response curves	
α_L	Longitudinal dispersivity	L
α_T	Transverse dispersivity	L
β	Parameter characterized by dose-response curves	
β	= 2 for radial flow and = 4 for parallel flow	
β_n	$= \prod^{(n/2)} / [(n/2)\,\Gamma\,(n/2)]$	
Δ	Small increment	
γ	Weighting factor	
φ	Uncertainty	
Γ	Gamma function	
Γ(-N,u)	Incomplete Gamma function	
Γ(0,u)	W (u) = Theis function	

Chapter 1

Introduction

1.1 PREAMBLE

Water of acceptable quality is both necessary for the improvement of the quality of life and essential in the maintenance of all forms of life. The limited number of water resources in South Africa has resulted in increased emphasis being placed on groundwater. Groundwater supply of acceptable quality and quantity is a very important factor in the development of communities. The availability of water for various uses is directly related to the management of water quantity, quality and/or the elimination of diseases. This thesis introduces a risk-based decision tool (DT) to be used for the management of groundwater.

A risk can be defined broadly as the probability that an adverse event will occur in specified circumstances. Effective decision-making involves the management of risks: the identification, evaluation, selection and implementation of actions to reduce risk. Risk assessment is a technique that provides such information to the manager, thereby facilitating the complex and integrated decisions required. Applications of risk assessments in determining the effects of exposure to contaminants have been institutionalised through legislation in the United States for over 20 years. Other countries such as Japan, Germany, the United Kingdom, the Netherlands and Canada also use some form of risk assessment in decision-making processes (Mazurek, 1996). While there is a growing demand for risk assessments in South Africa, they are yet to become a standard feature (Schwab and Genthe, 1998).

The aim of this research is to develop a DT to aid groundwater resource managers in the task of optimising the utilisation of groundwater. The DT will include:

- *Information concerning aquifer parameters*: Pumping test analysis methods have been developed primarily to investigate and characterise flow within idealised confined radial flow systems. Unfortunately these assumptions are usually invalid with regard to the shallow fractured rock aquifers in South Africa. Notable attempts have been made to expand pumping test methodologies. A worthwhile method to consider when analysing a pumping test was developed by Barker (1988), who generalised the Theis equation by including a term called the non-integer flow dimension, thereby making it applicable to arbitrary fractured confined aquifers.

- *Information concerning contaminant parameters*: Dispersivity is a scale-dependent property of an aquifer that determines the degree to which a dissolved constituent will spread in flowing groundwater. No detailed investigation was conducted concerning this parameter, but as it plays an important role in the movement of contaminated groundwater, it is briefly discussed.

  Although matrix diffusion can influence groundwater contamination, very little research has been conducted on this topic in South Africa. The project therefore includes laboratory matrix diffusion experiments. The results of these experiments are included in the DT.

- *A framework for risk assessments:* The project introduces tools based on fuzzy logic to assist in decision-making by systematically considering all possibilities. This tool takes into account the sustainability of a groundwater resource, the potential contamination of groundwater, human health risks and the impacts of changes in groundwater (quantity and/or quality) on aquatic ecosystems.

- *Methods for making cost-effective decisions*: Negative impacts can place heavy burdens on society and economics. Cost-benefit-risk assessments are therefore considered to define, compare and measure benefits and costs with regards to an impact.

- *Possibilities of remediation*: Remediation forms an important component of many groundwater investigations and experiments were therefore conducted, the results of which are included in the DT. The results provide the groundwater manager with an indication of the possible success of a remediation project.

1.2 SOUTH AFRICAN LEGISLATION

The Constitution of South Africa (Act No 108, 1996) states that everyone has the right to an environment that is not harmful to his or her well-being. It also states that everyone has the right to have the environment protected for the benefit of present and future generations through legislation that prevents pollution and ecological degradation, promotes conservation and secures ecologically sustainable development and use of natural resources while promoting justifiable economic and social development. The Constitution also states that everyone has the right to sufficient water.

During the last few years views on water management and protection in South Africa has changed radically. A prime example of these changes is the New National Water Act (Act No 36, 1998), which focuses on the principles of sustainability and equality. These principles take into account:

- the basic human needs of present and future generations,
- the need to protect water resources,
- the need to share water resources with other countries,
- the need to promote social and economic development through the use of water and
- the need to protect aquatic ecosystems.

Aquatic ecosystems are defined as the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs, lakes and wetlands and their fringing vegetation. Terrestrial biota, other than humans who are dependent on aquatic ecosystems, are also included in this definition (DWAF, 1996).

Other legislation that should be considered includes:

- *The Water Services Act* (Act No 108, 1997): The main objectives of this Act relevant to the research discussed in this document are to provide for:
  - the right of access to basic water supply and the right to basic sanitation necessary to secure sufficient water and an environment not harmful to human health or well-being,
  - the promotion of effective water resource management and conservation

- *The Environmental Conservation Act* (Act No 73, 1989) provides for the effective protection and controlled utilisation of the environment and for matters incidental thereto.

- *The National Environmental Management Act* (Act No 107, 1998) regulates co-operative environmental governance by establishing principles for decision-making matters affecting the environment.

- *Draft National Health Bill* (2001): This Bill promotes the protection, improvement and maitainance of the health of the population.

The final goal of this project is to provide South African groundwater managers with a tool incorporating some of the legislation discussed in this section.

1.3 THE RISK ASSSESSMENT FRAMEWORK *(Summarised from Schwab and Genthe, 1998)*

In this study, a tool that uses risk assessments to make decisions influencing groundwater management in South Africa is discussed. As a process of evaluating the potential for adverse impacts, risk assessment provides managers and the public with the means to surpass observations about relationships between events and their effects and, by so doing, to answer questions about what is safe and what is unsafe. However, *the priority in performing any risk assessment is clarifying the factual and scientific basis of the risks posed.* As such, both qualitative and quantitative evidence regarding the nature of the effects, their severity, and their reversibility or preventability must be examined. Figure 1-1 is a summary of the risk assessment framework.

Benefits of risk assessments include:

- A clear articulation of the risk. This includes the evaluation of the hazard and the extent and degree of harm that may result. Such an articulation allows risks to be balanced against one another.
- Reveal the uncertainties inherent in the assumption by forcing one to assess the strengths and weaknesses of each assumption in order to estimate the risk by means of the systematic process of a risk assessment. As such, a risk assessment provides a mechanism to allow transparent decisions to be made.

- Inherently flexible. A risk assessment can be targeted to a wide variety of situations and circumstances but can also be tailored to target a specific demographic group, geographic area, temporal period or situation.

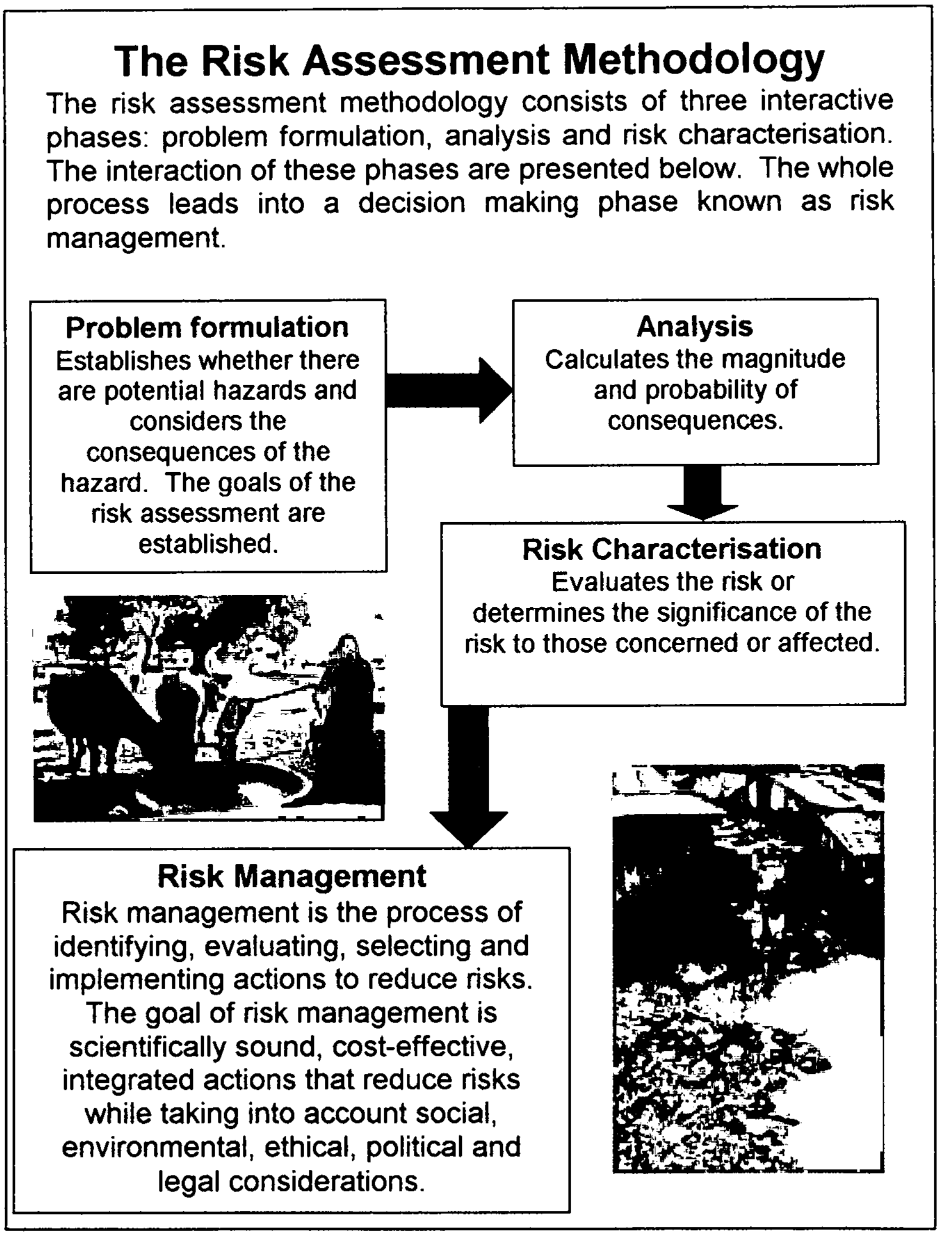


Figure 1-1. Risk assessment framework

There is not any single analytical method for combining information into an estimation of a risk but numerous risk assessment methods that span the spectrum from purely qualitative to highly complex mathematical models. The availability of data, finances and the required outcome will drive the choice of method.

The limitations of scientific information mean that some aspects of the assessment might involve qualitative aspects such as the use of professional knowledge. Risk assessments can therefore be seen as a *combination of science and judgment*.

1.4 STRUCTURE OF THIS DOCUMENT

The document is divided into 5 main sections:

- The first section (Chapter 2) discusses some new methodologies that can be used to gather information concerning the aquifer and the movement of contaminants. The methods include the analysis of pumping and tracer test data, and the study of dispersivities and matrix diffusion.

- The second section (Chapters 3 – 7) introduces the DT and discusses each of its components. The determination of the risks associated with impacts of natural and anthropogenic activities on groundwater quantity and quality, as well as the potential negative effects on human health, such as infection, toxic effects and the development of cancer, which result from contaminated groundwater, are discussed. As the Water Act (Act No 36, 1998) takes aquatic ecosystems into account, the risks of negative impacts of groundwater (quantity and quality) on aquatic ecosystems are included.

- The third section (Chapter 8) focuses on protecting and remediating groundwater. The protection of water resources is of such importance to the government that a whole chapter of the National Water Act (Act No 36, 1998) is dedicated to this topic. In this chapter, this protection is divided into two categories: measures to prevent the pollution of water resources and measures to remedy the effects of pollution of water resources. These two categories are discussed in this chapter.

- The fourth section (Chapter 9) discusses cost-benefit-risk analyses. Once the desired risk assessments have been completed, cost-benefit-risk analyses can be used to aid in decision-making regarding the management and remediation of a groundwater resource. A cost-benefit-risk analysis is defined as a set of procedures that originate from either an investment or the operation of a service.

- In the last section (Chapter 10), conclusions are drawn and recommendations provided.

Chapter 2

Aquifer and Contaminant Parameters

2.1 INTRODUCTION

Groundwater is becoming a very important water resource. In order to manage this resource correctly, the geohydrologist has to understand the groundwater system. Abstraction and tracer tests are two of the tools that can aid the geohydrologist in this process. A major objective in cost-effective groundwater protection and management is obtaining optimal value from information obtained from such tests. This chapter will focus on new methods suited for South African fractured aquifer conditions that can be used in the DT.

With increased human settlement and economic development, a number of undesirable substances may find their way into groundwater. It is important for geohydrologists to be able to assess and predict resource pollution. In order to achieve this, they must be able to understand and determine contaminant parameters. Therefore a part of this chapter is dedicated to contaminant parameters and methods to calculate them.

2.2 AQUIFER PARAMETERS

Pumping test analysis methods have been developed primarily to investigate and characterise flow within idealised confined radial flow systems. Unfortunately these assumptions are usually invalid in the shallow fractured rock aquifers in South Africa. The steep increase in drawdown towards the end of a pumping test (Figure 2-1) indicates that the boundary of a fracture has been reached and most of the flow to the borehole is from the matrix. Most analytical methods available today, for example Moench (1984), Cinco-Ley and Samaniego (1981 a&b) and Gringarten *et al.* (1974), could not be used to analyse this data set, as the methods do not include boundary effects. Notable attempts have been made to expand pumping test methodologies. A worthwhile method to consider when analysing a pumping test was developed by Barker (1988), where he generalised the Theis equation by including a term called the non-integer flow dimension, making it applicable to arbitrary fractured confined aquifers.

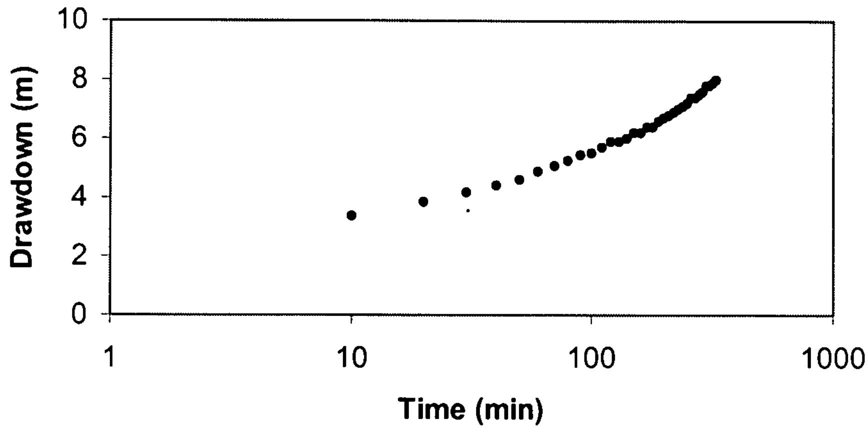


Figure 2-1. Pumping test results from a borehole in the Karoo Sequence. The borehole was pumped at a constant rate of 4L/s.

2.2.1 The Barker Method

One model to describe the flow behaviour in fractured rocks is the generalised radial flow (GRF) model proposed by Barker (1988), which is used to estimate the flow dimension of the fractured aquifer, the hydraulic conductivity and specific storage of the fracture system.

The equivalent system in Barker's GRF-model consists of a homogeneous and isotropic fracture system characterised by a hydraulic conductivity K_f and specific storage S_{sf}, in which the flow to the borehole is radial and n-dimensional. With this model, Barker presents a way of generalising the conventional models used for pumping test analysis for application to arbitrary flow dimensions. For instance, after generalising the Theis equation, it will describe the drawdown in an arbitrary fractured confined aquifer. The generalised Theis equation (Barker, 1988) is written as:

$$s(r,t) = \frac{Qr^{2N}}{4\pi^{1-N}K_f b^{3-n}}\Gamma(-N,u) \tag{2.1}$$

where,

u = $r^2S_{sf}/ 4K_ft$

b = Extent of flow region (thickness of flow region in case where n = 2)

N = $N = 1\text{-}n/2$

n = Non-integer flow dimension

K_f = Hydraulic conductivity of the fracture system

S_{sf} = Specific storage of fracture system

$\Gamma(-N,u)$ = Incomplete Gamma function

$\Gamma(0,u)$ = $W(u)$ = Theis function

r = The distance along the flow path

If n = 2 (meaning horizontal radial flow to an abstraction borehole) the parameter b is the thickness of the aquifer; for n = 1 (meaning linear flow to an abstraction borehole) the parameter b is the square root of the through-flow area and for non-integer values of n, b has no physical meaning.

It is obvious from Equation 2.1 that there is no unique solution. In order to determine a solution for the above equation it is necessary to fit values for K_f, S_{sf}, b, r and n. The rescaled range method provides a unique method to determine n.

2.2.2 The Hurst Exponent

2.2.2.1 Background (Summarised from Peters, 1996)

The Hurst Exponent (H) was defined by a hydrologist, Hurst, while working on studies of the Nile River. This exponent is also widely used in stock market predictions. H is determined by taking time series data and obtaining the gradient of the plot log(R/S) versus log(i) where

$$R = \text{Max}(X_{t,N}) - \text{Min}(X_{t,N})$$

$$\text{and} \quad X_{t,N} = \sum_{u=1}^{t}(e_u - M_N)$$

with

R = Range of X

$X_{t,N}$ = Cumulative deviation over N periods

e_u = Value of observation at time u

M_N = Average e_u over N periods

t = Time

S = Standard deviation

i = Number of observations

The Hurst exponent can be classified as:

- $H = 0.5$, which denotes a random data series.
- $0 \leq H < 0.5$, which denotes an anti-persistent time series
- $0.5 < H < 1$, which denotes a persistent time series

H is directly related to the non-integer fractal dimension (D) by $D = 1/H$.

2.2.2.2 Hurst Exponent and Pumping Tests

Pumping test data will normally exhibit persistent behaviour, implying that if the curve has been increasing for a period, it is expected to increase for another period, hence $0.5 < H < 1$. Pumping test data has a long memory component as each observation is correlated to some degree with the observations that follow.

Calculating H is based on a rescaled range analysis. This implies that the data series is divided into N periods, each containing the total number of observation points divided by N. The relationship between the period and the number of observations contained in the period is shown in Figure 2-2. It is important to note that the rescaled range analysis is dependent on the number of observations in a series, and the more observations the more accurate the results. When comparing results obtained for n using Equation 2.1 and then calculating D from the Hurst exponent, it is determined that $D \approx n$ (refer to Figure 2-3).

It is suggested that the following be taken into account to obtain the best results when determining n using Hurst:

- There must be at least 100 data points.
- The data points must be evenly spaced.
- The aquifer must be stressed.
- The observed data must not be noisy. If the data is scattered or noisy a smoothing function is included in the DT to ensure smooth data sets are used in the calculation of n.

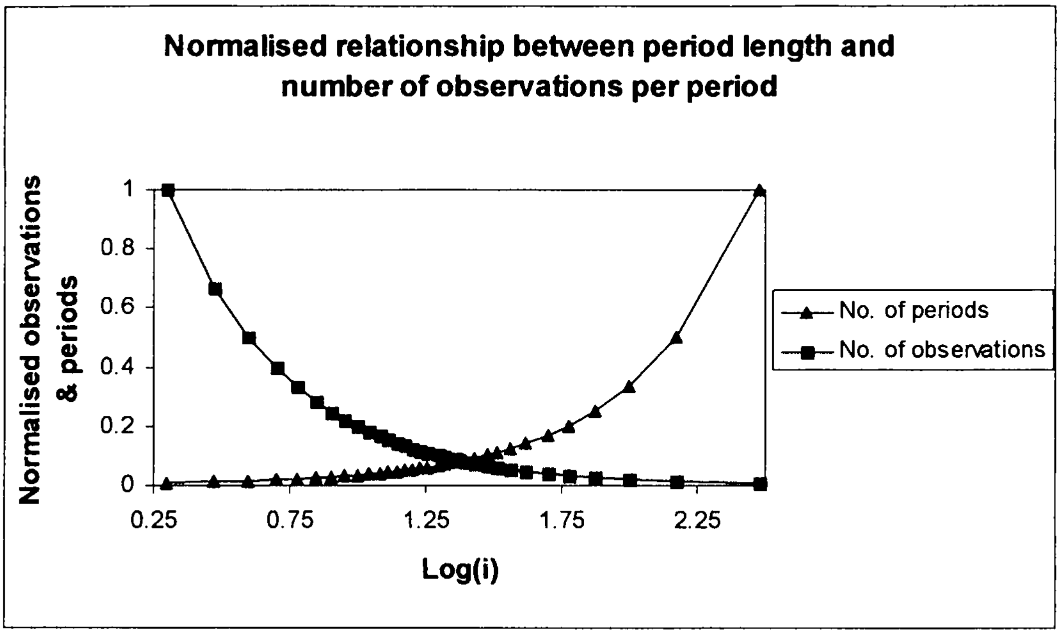


Figure 2-2. Normalised relationship between period length and number of observations per period.

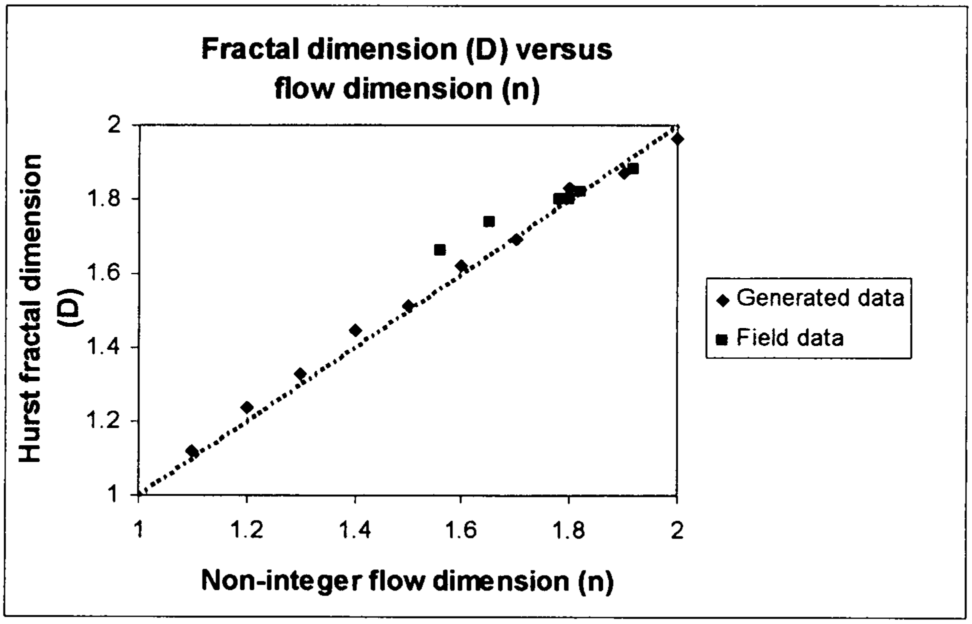


Figure 2-3. Fractal dimension determined using the Hurst exponent versus the non-integer flow dimension calculated with Barker's GRF-model.

2.2.2.3 Example

The Campus test site is located on the grounds of the University of the Free State, South Africa, and covers an area of approximately 180x192 m^2. The thickness of the aquifer on site is approximately 50 m. The aquifer is situated in the Karoo Sequence and the geology consists of sandstone, mudstone and shale deposited under fluvial conditions. Core samples indicate parallel horizontal fractures, the most significant of which is at a depth of 21 m.

Borehole UO5 was pumped for 0.63 L/s for a period of 6 hours. The pumping test data was recorded with a data logger with readings taken every minute. The pumping test data was analysed using both Barker's GRF-model (Figure 2-4) and the Hurst exponent (Figure 2-5).

The non-integer flow dimension determined by Barker's method is 1.85. The fractal dimension D calculated using the Hurst exponent is 1.876.

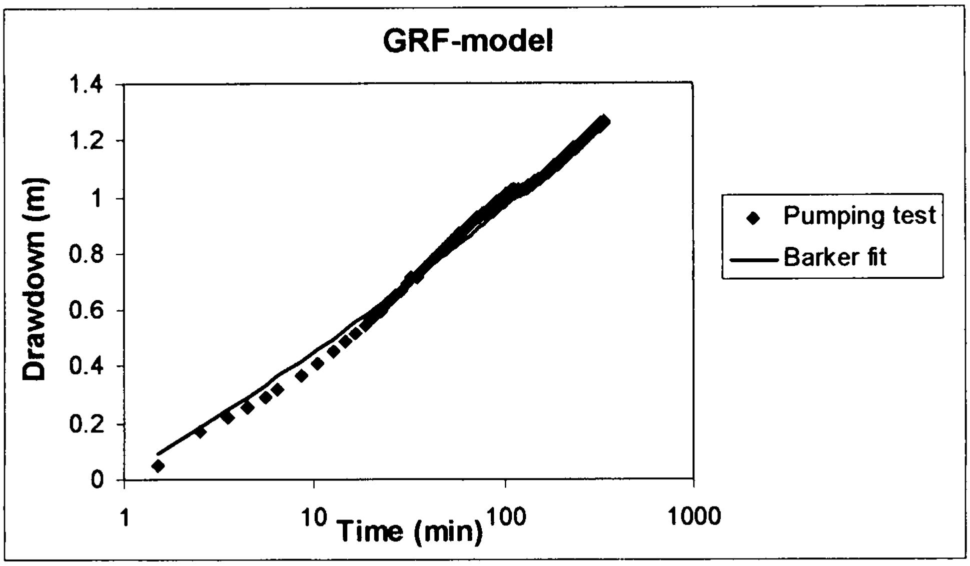


Figure 2-4. Barker analysis of UO5

It is important for the user to note that the software developed to determine the Hurst exponent is written in such a way that the user will always fit the late time data as shown in Figure 2-5.

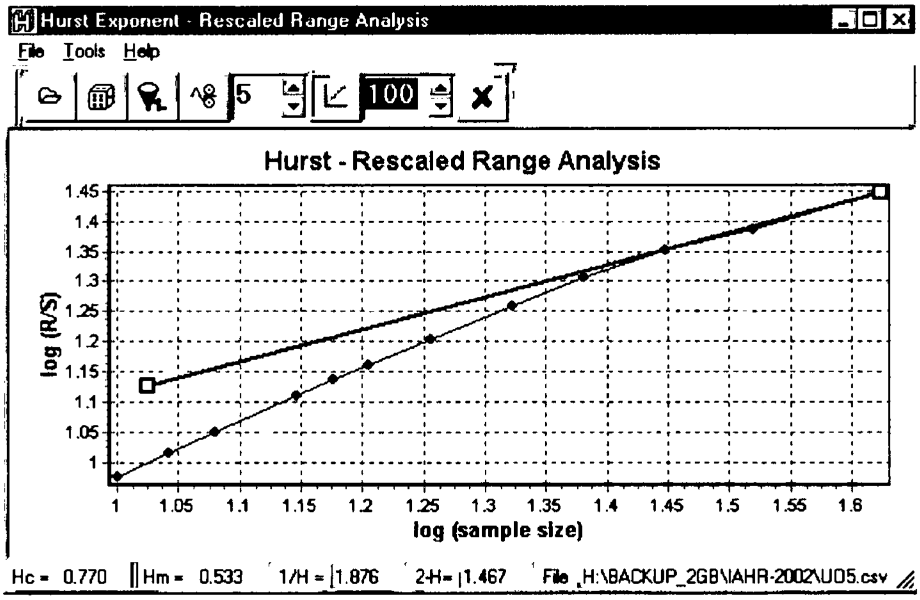


Figure 2-5. Hurst analysis of borehole UO5

2.2.2.4 *Discussion*

The Hurst exponent is calculated from pumping test data and is then inverted to give the non-integer flow dimension. The only drawback of this method is that it is data dependent – the more observations in a series, the more accurate the results will be. Experimental results indicate that data series with less than approximately 30 observations do not yield accurate results.

2.2.3 The GRF-model and Radius of Influence

Groundwater protection forms an important part of the DT. However to protect a borehole, the radius of its influence needs to be determined. Therefore this section discusses borehole radius of influence calculations.

When considering porous flow (n = 2) the radius of influence can be determined using the Cooper-Jacob equation (Kruseman and De Ridder, 1991) where:

$$s = \frac{2.3Q}{4\pi KD} \log \frac{2.25KDt}{r^2 S} \tag{2.2}$$

where

s = The drawdown measured a distance r from the borehole

Q = The constant discharge in a borehole

KD = The transmissivity of the aquifer

S = The storage coefficient of the aquifer

t = The time since pumping started

However to determine the full radius of influence s must equal zero. Therefore Equation 2.2 becomes:

$$0 = \frac{2.3Q}{4\pi KD} \log \frac{2.25KDt}{r^2 S} \tag{2.3}$$

by changing the subject of the formula in Equation 2.3, the following equation for the radius of influence r_e, is obtained:

$$r_e = 1.5\sqrt{\frac{KDt}{S}}$$

Similarly the GFR-model can be used to determine the radius of influence for fractured conditions. For large t values Equation 2.1 can be approximated by (Bangoy and Drogue, 1993):

$$s = \frac{Q}{4\pi^{1-N} K_f b^{3-n} N}\left[\left(\frac{4K_f t}{S_{sf}}\right)^N - \Gamma(1-N) r^{2N}\right]$$

When determining the radius of influence the drawdown is zero, therefore the above equation is re-written as:

$$0 = \frac{Q}{4\pi^{1-N} K_f b^{3-n} N}\left[\left(\frac{4K_f t}{S_{sf}}\right)^N - \Gamma(1-N) r^{2N}\right]$$

Implying

$$\left[\left(\frac{4K_f t}{S_{sf}}\right)^N - \Gamma(1-N) r^{2N}\right] = 0$$

The following is obtained by making r_e the subject of the formula:

$$r_e = 2\sqrt{\frac{K_f t}{S_{sf}}}\sqrt{\frac{1}{[\Gamma(1-N)]^{1/N}}}$$

by substituting $\Gamma(1\text{-}N) = \text{-}N\Gamma(\text{-}N)$ and $\frac{1}{\Gamma(-N)} = -Ne^{-0.577N}\prod_{m=1}^{\infty}\left[\left(1-\frac{N}{m}\right)e^{N/m}\right]$

(Abramowitz and Stegun, 1972) in the above equation the following is obtained:

$$r_e = 2\sqrt{\frac{K_f t}{S_{sf}}}\sqrt{e^{-0.577}\left[\prod_{m=1}^{\infty}\left(1-\frac{N}{m}\right)e^{1/m}\right]^{1/N}} \qquad (2.4)$$

Equation 2.4 can now be approximated as

$$r_e = 2\sqrt{\frac{K_f t}{S_{sf}}}\sqrt{e^{1-0.577}(1-N)^{1/N}} \qquad (2.5)$$

for $N \neq 0$ and $N < 1$.

2.3 CONTAMINANT PARAMETERS

2.3.1 Dispersivity

Dispersivity is a scale-dependent property of an aquifer that determines the degree to which a dissolved constituent will spread in flowing groundwater. No in-depth investigation was conducted concerning this parameter, although it is important in the movement of contaminated groundwater and as such, is briefly discussed. Figure 2-6 is a graph depicting field-scale dispersivities versus the migration distance, plotted from numerous field measurements. From this graph it can be determined that the relationship between dispersivity and migration distance lies in a zone around the following line:

$$\alpha_L = 0.1 \times L \qquad (2.6)$$

where

α_L = Dispersivity

L = Migration distance of the contaminant

Equation 2.6 is based on a small set of data and will therefore only be used to estimate dispersivities in the intermediate assessments. Low to medium confidence is attached to these results. In Section 2.3.3 a more accurate method for calculating dispersivity is discussed.

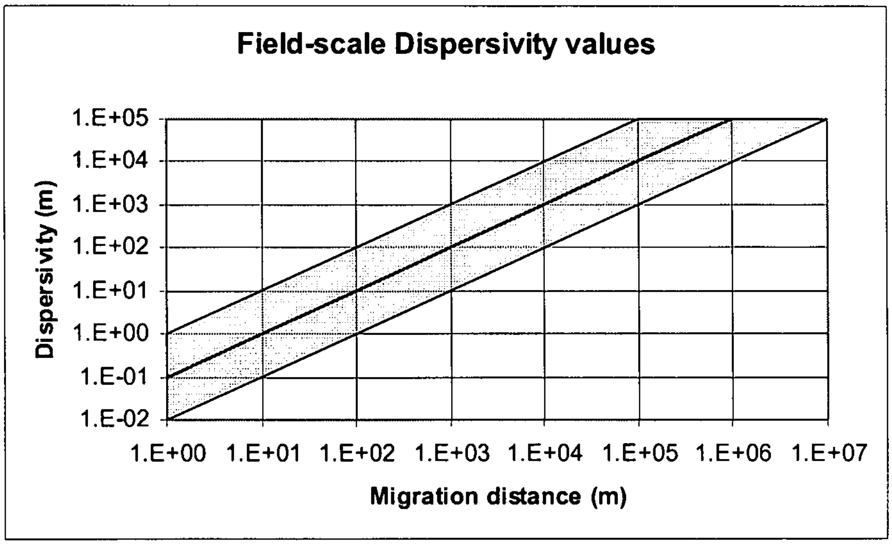


Figure 2-6. Estimation of field-scale dispersivity values *(taken directly from Spitz and Moreno, 1996)*

2.3.2 Matrix Diffusion

2.3.2.1 General

The role of matrix diffusion in groundwater contamination and remediation is in many cases either ignored (Maloszewki and Zuber, 1993) or not fully understood. However more and more geohydrologists are recognising the importance of matrix diffusion (Feenstra *et al.*, 1984; Maloszewki and Zuber, 1993). The aim of the research discussed in this section is to obtain, by means of laboratory experiments, a better understanding of matrix diffusion and the role it plays in the contamination of many of the fractured rock aquifers in South Africa.

Foster (1975) was the first to draw attention to the effects of matrix diffusion on contaminant behavior in fractured rock aquifers. The process of solute diffusion from a fracture to the adjacent matrix is illustrated in Figure 2-7, which schematically shows a constant solute source of constant concentration C_0 transported through the fracture. The effect of matrix diffusion is to provide solute 'storage' with the rate of change in storage within the matrix related to Fick's second law of diffusion. The solute becomes entrapped in the matrix until the concentration gradient reverses. This matrix diffusion results in retardation, causing the bulk of the solute to move at a lower average velocity than the flowing groundwater (Hoag and Price, 1997).

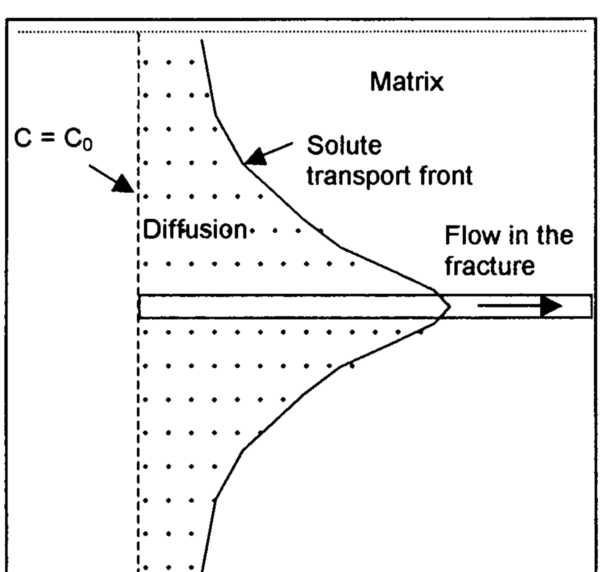


Figure 2-7. Schematic diagram of matrix diffusion in a fracture

2.3.2.2 Methdology

Feenstra *et al.* (1984) discusses a method to determine matrix diffusion in a laboratory. A flat disc of core is dried and then placed in acrylic diffusion cells (Figure 2-8).

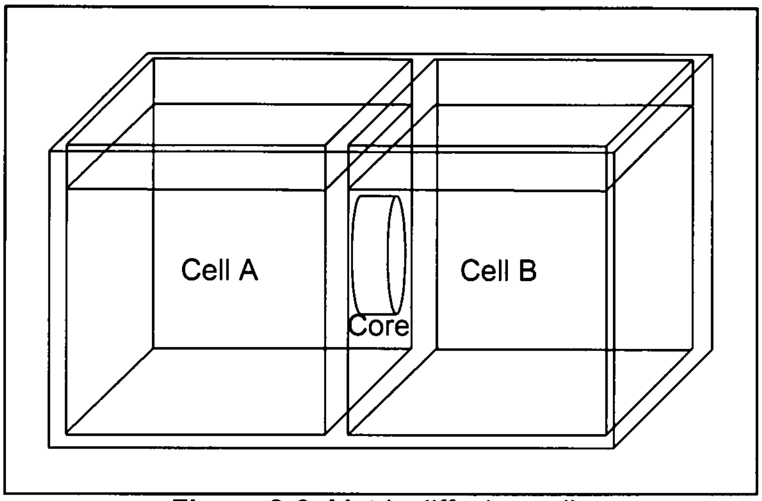


Figure 2-8. Matrix diffusion cells

Deionized water is placed in one of the cells for several days until the water emerges through the sample. Deionized water is then placed in the other cell as well to ensure that the disc is completely saturated. Both cells are then emptied and cell A is filled with a solute, while cell B is filled with deionized water. The diffusion of the solute through the core disc increases the solute concentrations in cell B. The matrix diffusion coefficient can be determined for the core by considering the transfer of mass from one cell to the other through the core disc as (Feenstra *et al.*, 1984):

$$D_{(t_2 \rightarrow t_1)} = \frac{(C^B_{t_2} - C^B_{t_1})LV^B}{AC^A(t_2 - t_1)} \tag{2.7}$$

where

$D_{(t2\text{-}t1)}$	=	The effective diffusion coefficient measured between time t_1 and t_2
C^A	=	The concentration in compartment A
C^B	=	The concentration in compartment B
V^B	=	The volume of solution in compartment B
A	=	The area of the core disc
L	=	The thickness of the core disc

2.3.2.3 Experiments

A number of matrix diffusion experiments were conducted at the Institute for Groundwater Studies' laboratory in Bloemfontein. These experiments were conducted on sandstones, shales and a quartzite using various concentrations of sodium chloride (NaCl) and sodium sulphate (Na_2SO_4). These experiments will be discussed in the following subsections but a basic experiment will firstly be discussed to familiarise the reader with the methodology.

A basic experiment

The effective matrix diffusion coefficient was calculated for NaCl, which is considered to be a non-reactive solute. The experiment was conducted on a flat disc of fine white sandstone with a porosity of approximately 4.4%. The core was 5 mm thick. In order to determine the effective diffusion coefficient, cell A was filled with 1 g NaCl per 100 ml deionized water. Cell B was filled to the same level with deionized water. The diffusion of the NaCl through the sandstone sample resulted in an increase of NaCl concentrations in cell B. The electrical conductivity (EC) values in both cells were measured regularly during the 13-day experiment. The increase in EC values in cell B is shown in Figure 2-9.

The diffusion coefficient was calculated using Equation 2.7. The coefficient was calculated for successive time intervals until a constant value was achieved. The value obtained was 3.3 x 10^{-9} m^2/h.

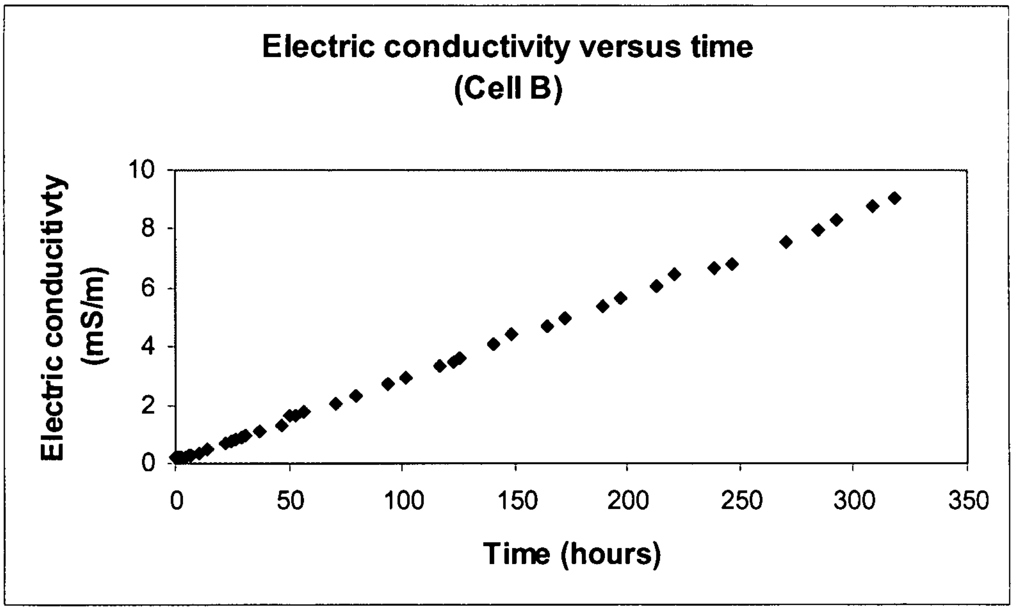


Figure 2-9. Increase in electrical conductivity values with time in Cell B.

Matrix diffusion coefficients and porosity

The same matrix diffusion experiment was performed on various sandstones, shales and one quartzite. The cores were all approximately 5 mm thick. A solute of 1 g NaCl/10 ml deionized water or 1 g Na_2SO_4/10 ml deionized water was added to cell A, while deionized water was added to cell B. The results of the experiments can be seen in Figure 2-10. The calculated matrix diffusion coefficients are documented in Table 2.1.

Table 2.1: Matrix diffusion coefficients

Formation	Porosity (%)	D (m^2/h) NaCl	D (m^2/h) Na_2SO_4
Sandstone (coarse	10.9	2.28×10^{-7}	1.89×10^{-7}
Sandstone (medium	7.1	8.02×10^{-8}	2.68×10^{-8}
Sandstone (medium	6.1	6.82×10^{-8}	2.41×10^{-8}
Sandstone (fine grain)	4.4	3.34×10^{-9}	2.41×10^{-8}
Shale	1.12	1.88×10^{-7}	1.87×10^{-8}
Shale	0.92	1.78×10^{-7}	2.19×10^{-8}
Shale	0.83	7.59×10^{-7}	-
Quartzite	0.19	1.80×10^{-7}	-

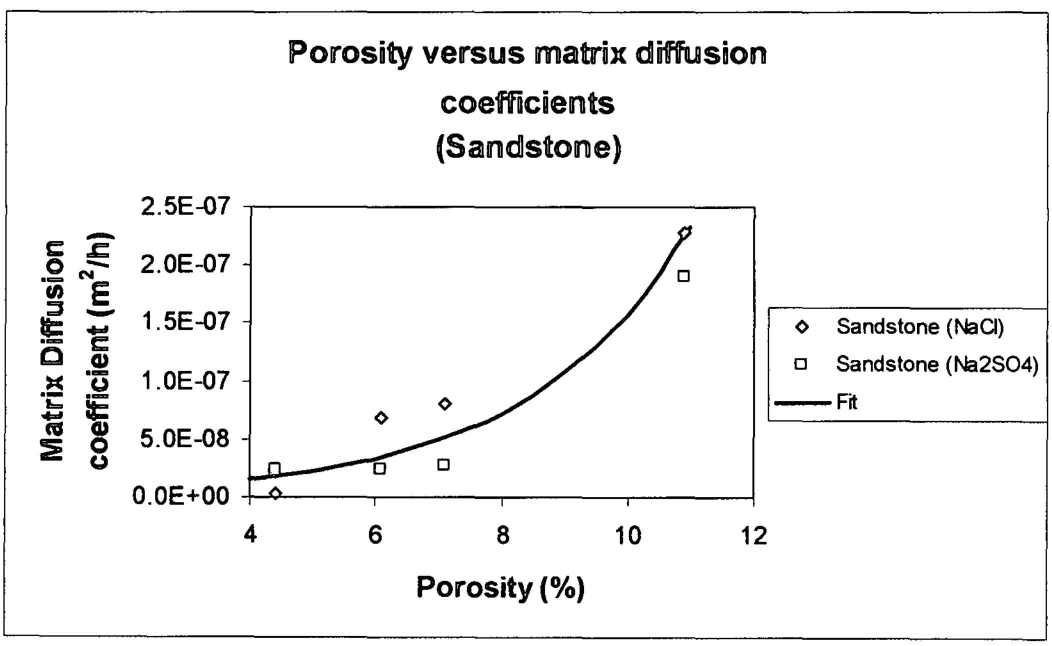


Figure 2-10 (a). Relationship between porosity and matrix diffusion coefficients for sandstones

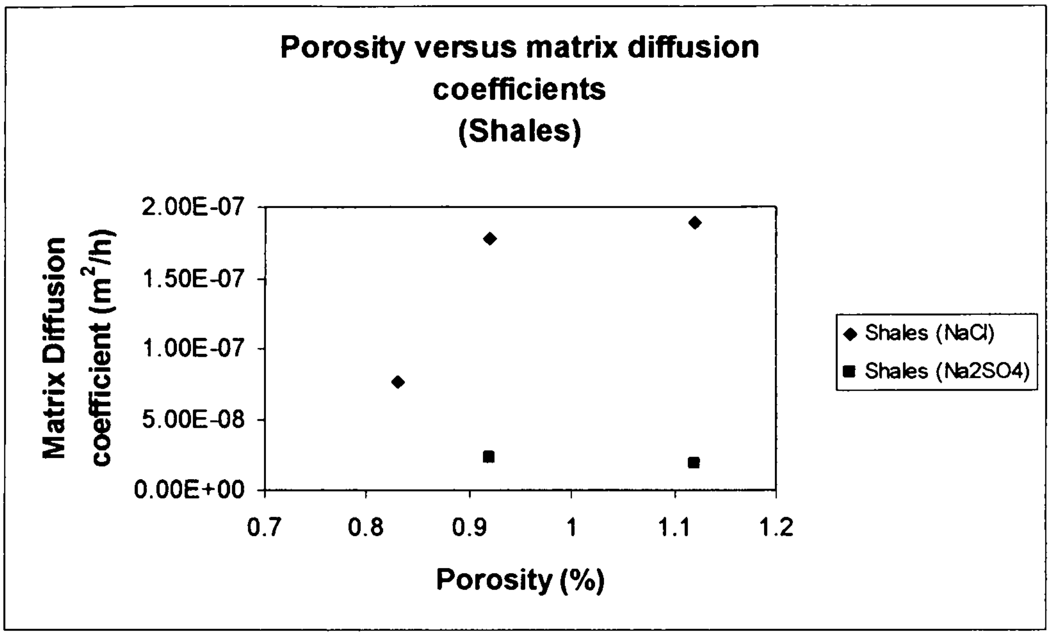


Figure 2-10 (b). Relationship between porosity and matrix diffusion coefficients for shales

From Figure 2-10(a), a relationship between porosity and matrix diffusion coefficients for sandstones can be determined as:

$$D = 3.2x10^{-9} \exp^{0.39n_e}$$

where D is the matrix diffusion coefficient calculated in m^2/h and n_e is the porosity. This equation is based on very little data and numerous experiments will have to be conducted to validate this result. No relationship between porosity and the matrix diffusion coefficient can be determined from Figure 2-10 (b) as there is insufficient data. The matrix diffusion coefficients do not show the same trends as those in the sandstones. This may be a result of either interactions between the shales and the concentrations of NaCl and Na_2SO_4 and/or secondary porosity. Due to difficulties in obtaining quartzite core only one type of quartzite was used in the experiments. It is interesting to note, however, that even though the porosity of the quartzite is low, the diffusion coefficient is relatively high. This is most probably due to the fact that there is very little interaction between the quartzite and NaCl or Na_2SO_4.

Matrix diffusion coefficients for various concentrations

It is sometimes easier to understand diffusion coefficients when expressing them in terms of mass of contaminant that passes from the fracture into the matrix. Once the matrix diffusion coefficient has been determined, Equation 2.7 can be used to calculate the mass passing through the core in an hour. To demonstrate this, three matrix diffusion experiments were performed on the same sandstone using different concentrations. The core radii were 30 mm in all cases and the thickness was 5 mm. The matrix diffusion coefficients, together with the concentrations in cell A and the transfer rate of NaCl, are listed in Table 2.2.

Table 2.2: Comparison of matrix diffusion values for various concentrations

Initial NaCl concentration in cell A (g/10 ml deionized water)	Matrix diffusion coefficient (m^2/h)	NaCl per area core (mg/h)
0.5	3.34×10^{-9}	0.1
1.0	2.12×10^{-8}	1.2
2.0	4.99×10^{-8}	5.6

An indication of the quantity of solute that can diffuse into a rock matrix, the values in Table 2.2 are used to calculate the amount of NaCl that can diffuse via fractures in varying areas (Table 2.3).

Table 2.3: Amount of NaCl that can diffuse into a rock matrix using values listed in Table 2.2

Size of fracture (m x m)	Amount of NaCl that can diffuse into matrix (g/h) when D is		
	3.34×10^{-9}	2.12×10^{-8}	4.99×10^{-8}
1 x 1	0.0071	0.085	0.4
10 x 10	0.707	9	40
50 x 50	18	212	989
100 x 100	71	848	3958

When plotting the values listed in Table 2.2 one can see an "almost" linear relationship between the initial NaCl concentrations in cell A and the matrix diffusion coefficients (Figure 2-11 (a)). A similar relationship can be seen when comparing the concentration in cell A and NaCl movement through the core (Figure 2-11(b)).

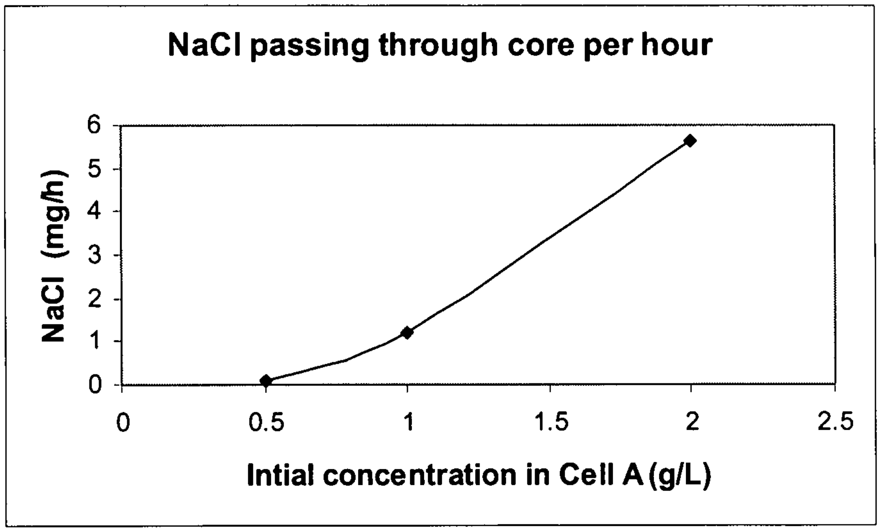


Figure 2-11(a). Amount of NaCl passing through sandstone core per hour for various initial NaCl concentrations in cell A.

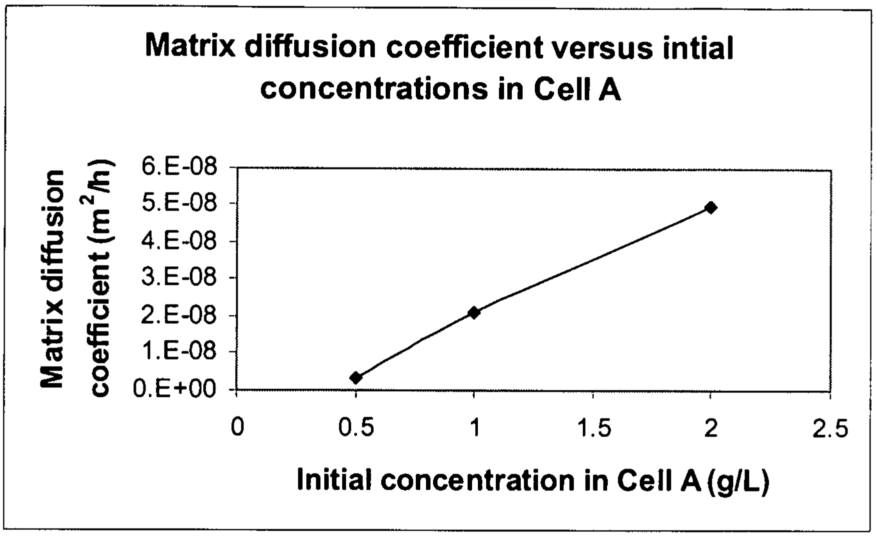


Figure 2-11(b). Increase in matrix diffusion coefficients as initial concentrations of NaCl increase in cell A.

Determining the difference between matrix diffusion in the horizontal and vertical directions

All afore-mentioned matrix diffusion coefficients have been determined for horizontal slices and, therefore, in the vertical direction (refer to Figure 2-12). However, the question remains as to whether or not there is a difference between horizontal and vertical matrix diffusion values. A number of experiments on sandstones were conducted to study this aspect.

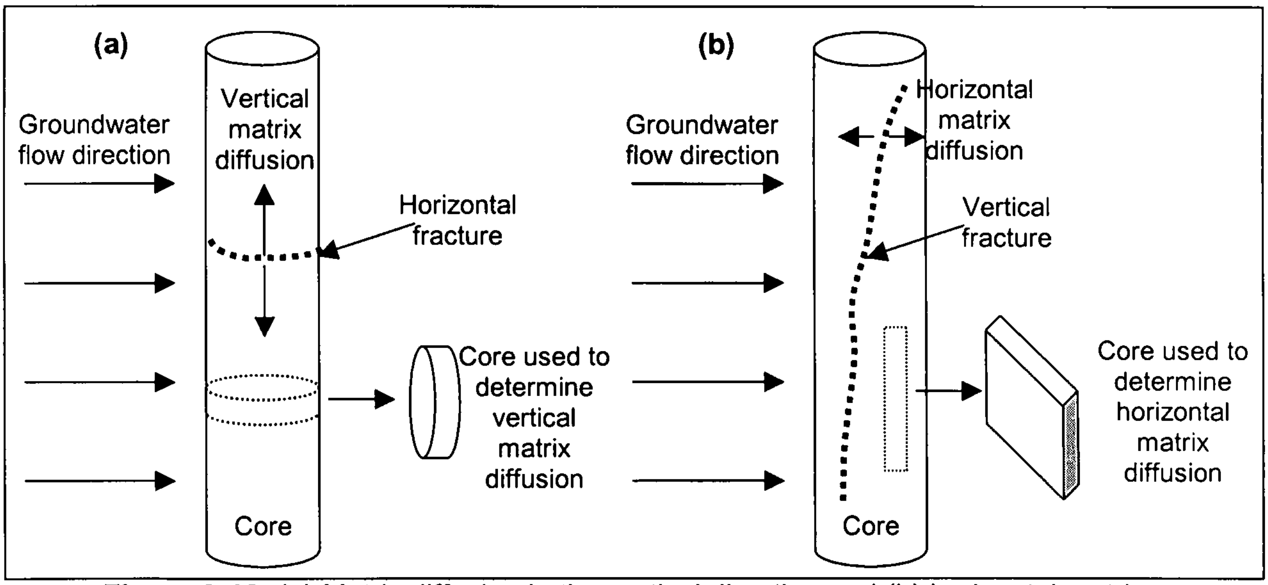


Figure 2-12. (a) Matrix diffusion in the vertical direction and (b) horizontal matrix diffusion

The results of these experiments are listed in Table 2.4.

Table 2.4: Horizontal versus vertical matrix diffusion coefficients

Horizontal coefficient	Vertical coefficient
9.95×10^{-8}	3.31×10^{-8}
8.24×10^{-7}	2.74×10^{-7}
8.92×10^{-7}	2.12×10^{-8}

In all cases the matrix diffusion coefficients in the horizontal direction are greater than those in the vertical direction. The degree of difference varies from sandstone to sandstone and is most probably dependent on factors such as the fracture characteristics and mineral composition of the sandstone.

The influence of pH on the matrix diffusion process

Appelo (2000) states that low pH values would increase the retardation of sulphates and that sulphates are sorbed when the pH is lower than 5. Three experiments were performed to test this theory, one on a sandstone and two on shales. A concentration of 1g Na_2SO_4/10 ml deionized water was added to cell A. The experiments were run under normal conditions (pH = 7) for a couple of weeks and then HNO_3 was added to cell A. At this point the pH in the cell dropped to 4. The results of one of these experiments can be seen in Figure 2-13. The results of the other two experiments show the same behavior.

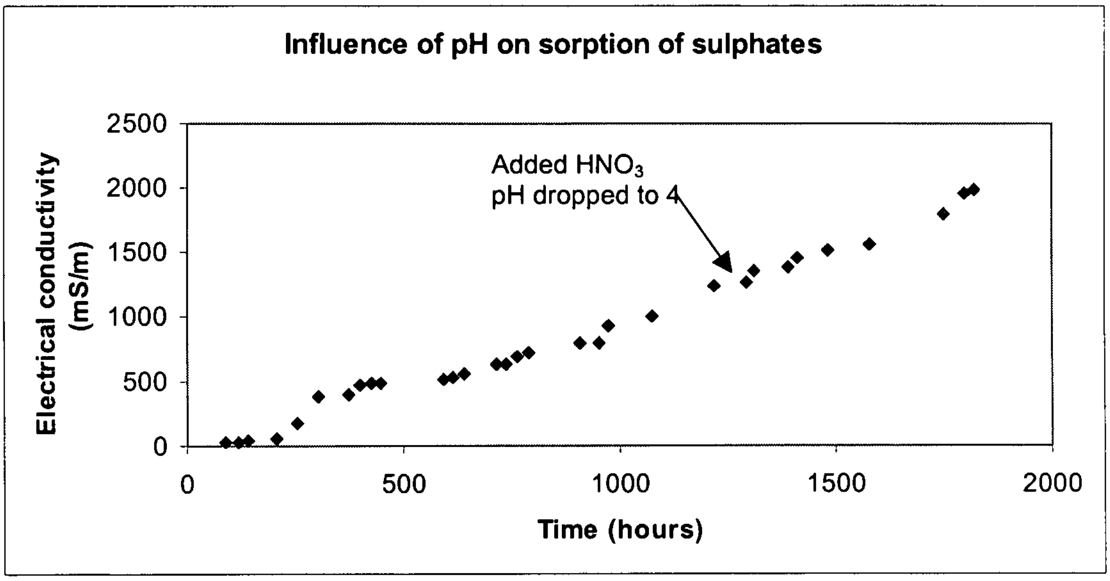


Figure 2-13. The impact of pH on the sorption of sulphates

The results indicate that pH does not seem to have an effect on the sorption of sulphates in the experiments conducted at the Institute for Groundwater Studies. However, these results must be verified.

Discussion

The experiments discussed in this section provide an indication of the impacts of matrix diffusion. Table 2.3 provides an idea of the amount of pollution that can diffuse from a fracture acting as a conduit for pollutants into the adjacent rock matrix. It is important to note that the results discussed in this section are based on a few experiments and must be verified. Unfortunately, the duration of each experiment exceeds one month. Combined with many problems such as cells that leaked and EC probes which did not read correct values, especially in cell A where the EC values were extremely high, it was not possible to conduct more experiments within the time frame of this study.

2.3.3 Tracer Tests *(Summarised from Van Tonder et al., 2001)*

2.3.3.1 General

For the investigation of risk assessment and remediation of groundwater contamination, it is important to estimate transport parameters such as groundwater velocity, effective (or kinematic) porosity and dispersion. For high confidence results, these parameters have to be analysed from field tests, known as tracer tests. As tracer tests under natural conditions, with several observation boreholes, require much time and are costly, different single-well and dual-well tracer tests were explored, two of which will be discussed in this section.

2.3.3.2 Single Well Injection-withdrawal Test

To conduct a single well injection-withdrawal test, a tracer is introduced to the standing water column of the test borehole and allowed to drift away, under natural gradient, from the borehole. The test borehole is pumped until the tracer plume is retrieved. Groundwater flow velocity is then calculated based on the amount of pumping needed to recover the tracer.

$$v = \frac{\left(\dfrac{Qt_p}{n_e b^{3-n}\beta_n}\right)^{1/n}}{t_d} \quad \text{and} \quad \beta_n = \frac{\pi^{n/2}}{\frac{1}{2}n\Gamma\left(\frac{n}{2}\right)}$$

where

Q = Pumping rate during recovery of tracer

n_e = Effective porosity

t_p = Time elapsed from start of pumping until the centre of mass of the tracer is recovered

t_d = Time elapsed from the injection of tracer until the centre of mass of the tracer is recovered

The effective porosity can be calculated:

$$n_e = \left[\frac{\beta_n b^{3-n} \left(K \frac{dh}{dl} t_d \right)^n}{Qt_p} \right]^{\frac{1}{n-1}}$$

where

dh/dl = Hydraulic gradient

2.3.3.3 Radial Convergent Test

Pumping a borehole until steady state conditions are reached creates a radial convergent flow field. A tracer is then quickly introduced into an injection borehole in the vicinity of the pumping borehole in such a way that minimum disturbance of the flow field is caused, while the tracer breakthrough curve is monitored at the pumping borehole. Analyses of the resulting breakthrough curves yield estimates of the effective porosity, aquifer dispersivity and groundwater velocity. The convergent test is attractive because it is theoretically possible to recover the tracer from the aquifer. Furthermore, it more closely represents reality as groundwater pollution often occurs in the vicinity of pumping boreholes where radial flow fields are present. The approximate solution for converging radial flow with a pulse injection is given by:

$$C(r,t) = \frac{\Delta M}{2Q\sqrt{\pi \alpha_L v t^3}} \exp\left[-\frac{(r - vt)^2}{4D_L t} \right]$$

where

ΔM = Injected mass of tracer per unit section

α_L = Longitudinal dispersivity

D_L = Longitudinal dispersion coefficient

v = v_f; groundwater velocity under forced gradient

Q = Pumping rate of the borehole

r = Distance between the two boreholes

The flow velocity under forced gradient v_f and dispersivity can be estimated by fitting the equation to the data of the breakthrough curve. The effective porosity can then be estimated using the following equation:

$$n_e = \frac{Q}{vA}$$

where A is the through flow area:

$$A = \frac{2\pi^{n/2} r^{n-1} b^{3-n}}{\Gamma\left(\frac{n}{2}\right)}$$

Chapter 3

The Decision Tool

3.1 BACKGROUND

During the last few years, the thinking concerning the management and protection of water resources has changed radically in South Africa. A *resource directed measures* (RDM) team was initiated to ensure that certain aspects of the National Water Act would be implemented. The task of this team included:

- To devise a system of consistent rules to guide decision-making about water resources on a national basis.
- The national system should allow transparency, accountability and long-term goal-setting to be incorporated into water resources management.
- Water resources that need to be improved can then be identified and the necessary control measures can be implemented to meet the requirements (MacKay, 1998).

Depending on the importance and sensitivity of the groundwater resource, there are various levels of determinations:

- *Desktop estimate* – a short planning estimation, with very low confidence attached to the results. This should not take longer than a few hours to complete.
- *Rapid determination* – an extension of the desktop study taking in the order of a few days to complete. Low levels of confidence are attached to the results.
- *Intermediate determination* – this estimation should take approximately 2 months to complete and includes specialist field studies. Medium levels of confidence are attached to the results.
- *Comprehensive determination* – a relatively high confidence is attached to this determination and includes extensive field data collection by specialists. The study should be conducted over a period of at least 8 - 12 months.

To align the decision tool with South African legislation, a tiered approach was followed. The first tier is a rapid assessment in which only existing data is required and it produces low confidence results. This assessment should be completed within a few hours. It is intended to give the assessor a guideline of the risks and cost implications involved. The next tier is an intermediate assessment. The first step in the intermediate assessment is to collect all relevant data. Data requirements include recharge values, aquifer and contaminant parameters, as well as health and ecological information. Most of the general information will be obtained from the database included in the DT software, but it is sometimes necessary to have site-specific data. This assessment should not take longer than 1 – 4 weeks to complete. The confidence attached to these results is low to medium. Finally a comprehensive assessment requires extensive field investigations and specialist studies. Once all necessary data has been collected, it will be analysed. The whole process should take between 1 – 6 months. The confidence attached to the comprehensive assessment should be medium to high.

3.2 THE FUZZY LOGIC BASED SYSTEM *(Summarised from Van der Werf and Zimmer, 1997)*

Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth; truth values between *completely true* and *completely false*. It was proposed by Zadeh (1965) to deal with uncertainty.

In classical set theory, an element is either in a set or it is not. For example, if a subset A consists of pesticides with a maximum field half-life of 20 days, a particular pesticide can be classified as a member or not a member of a subset. If, however, A is defined to be the subset of 'non-persistent' pesticides, then it is more difficult to determine if a specific pesticide is in the subset. If one decides that only pesticides with a maximum field half-life of 20 days are in the subset, then a pesticide with a 21-day half-life cannot be classified as non-persistent even though it is *almost* non-persistent. The use of fuzzy set theory is particularly compelling because available values for field half-life and several other relevant variables are imprecise and/or uncertain.

Fuzzy set theory addresses this type of problem by allowing one to define the degree of membership of an element in a set by means of a *membership function*. For classical sets, the membership function only takes 2 values: 0 (non-membership) and 1 (membership). In fuzzy sets the membership function can take any value from the interval [0,1]. The value 0 represents complete non-membership, the value 1 represents complete membership and the values in between are used to represent partial membership (transitional zone).

For input variables two fuzzy subsets F (favourable) and U (unfavourable) are defined. The membership functions are based on *available data* or *expert knowledge*. Many membership functions are sine shaped in the transitional interval. For example consider the leachability of pesticides. If the groundwater ubiquity score is greater than 2.8 then a membership of 1 is assigned and the values are totally unfavourable. Pesticides are classified as non-leachers if the ubiquity score is less than 1.8. A membship value of 0 is given for the fuzzy subset U and a membership value of 1 is given for the fuzzy subset F. The class of borderline components between 1.8 and 2.8 falls within the transition zone in which the membership value for F decreases from 1 (ubiquity score = 1.8) to 0 (ubiquity score = 2.8) and the membership value for U increases from 0 to 1. The functions characterising F and U are therefore complementary (Figure 3-1).

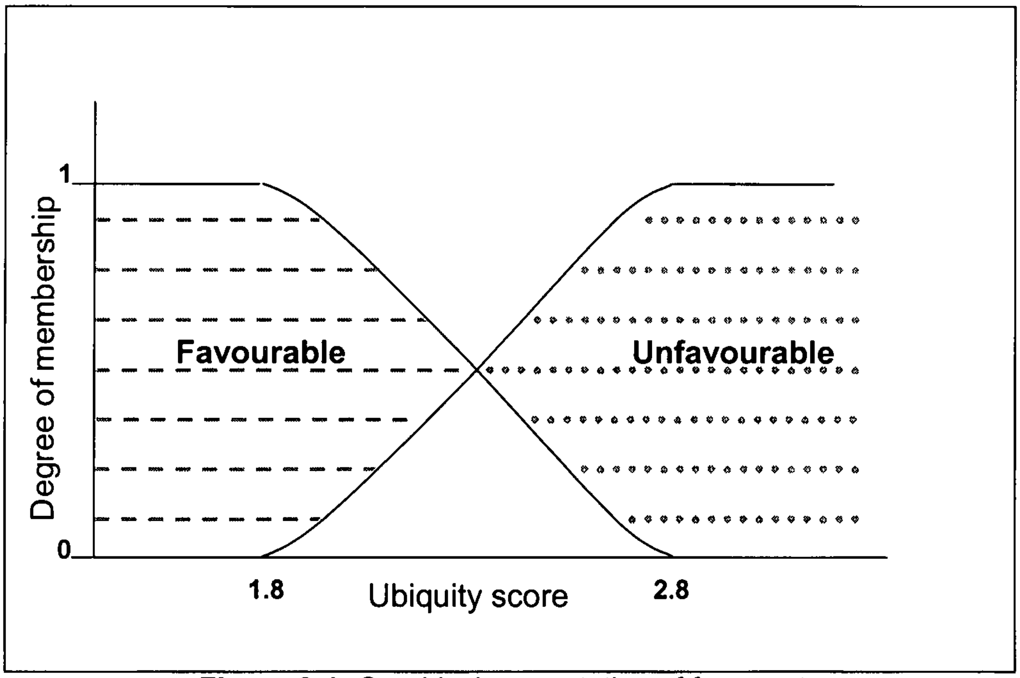


Figure 3-1. Graphical presentation of fuzzy sets

For each component of the tool a set of decision rules is formulated attributing values between 0 and 1 to an output variable, according to the membership of its input variables to the fuzzy subsets F and U. Sugeno's (1985) inference method is used to compute the decision rules and risk. The decision rules take the form:

If x_1 is A_{11} and x_2 is A_{12} then y is B_1

If x_1 is A_{21} and x_2 is A_{22} then y is B_2

Where x_j (j = 1, 2) is an input variable (eg half-life), y is an output variable (eg value of the component). A_{ij} is a fuzzy set and B_i is a number known as the conclusion of the rule.

Let x_1' and x_2' be the values taken by x_1 and x_2, and $A_{ij}(x_j')$ the membership value of x_j' to the fuzzy set A_{ij} (given by the membership function that defines A_{ij}). The truth values are then defined as:

$$W_1 = \min(A_{11}(x_1'),A_{12}(x_2'))$$

$$W_2 = \min(A_{21}(x_1'),A_{22}(x_2'))$$

Where min is the 'minimum value of'. The first rule infers W_1B_1 and the second one infers W_2B_2. The final risk can then be defined as

$$\text{Risk} = (W_1B_1 + W_2B_2)/(W_1 + W_2) \qquad (3.1)$$

The above explanation is easier to understand when explained by means of an example. Assume (only to illustrate the approach) that the risk of contamination from a pesticide depends on two input variables: rate of application and pesticide half-life. For both input variables membership to fuzzy sets F and U have to be defined. Assume that the experts say that a low rate of application and a short field half-life are favourable, whereas a high rate of application and a long field half-life are unfavourable. For the rate of application complete membership to the fuzzy set F is if the rate of application < 0.001 $kgha^{-1}$ and complete membership to the fuzzy set U if the rate of application > 2 $kgha^{-1}$; for field half-life complete membership to F is if field half-life < 1 day and complete membership to U if field half-life > 120 days (Figure 3-2).

In this example, there are 2 input variables and two fuzzy subsets for each input variable therefore 4 situations may occur, as reflected in the decision table (Table 3.1). These rules reflect expert knowledge and/or expert judgement. The first line of the table reads as *if the rate of application is favourable and the field half-life is favourable then the rule conclusion is 0.* As can be seen from Table 3.1, when both input variables are F, the rule conclusion is 0, when both input variables are U the rule conclusion is 1. When one input variable is F and the other is U the rule conclusion is 0.5.

Table 3.1: Summary of decision rules describing the effect of input variables rate of application and field half-life on risk of contamination

Rate of application	Field half-life	Conclusion
F	F	0.0
F	U	0.5
U	F	0.5
U	U	1.0

Once the membership functions and decision rules have been defined, the output for the risk of contamination from the pesticide can be defined. Assume that atrazine is applied at 1.5 $kgha^{-1}$ and that its field half-life is 60 days. The membership functions defined allow one to calculate the degree of membership for this pesticide (Figure 3-2).

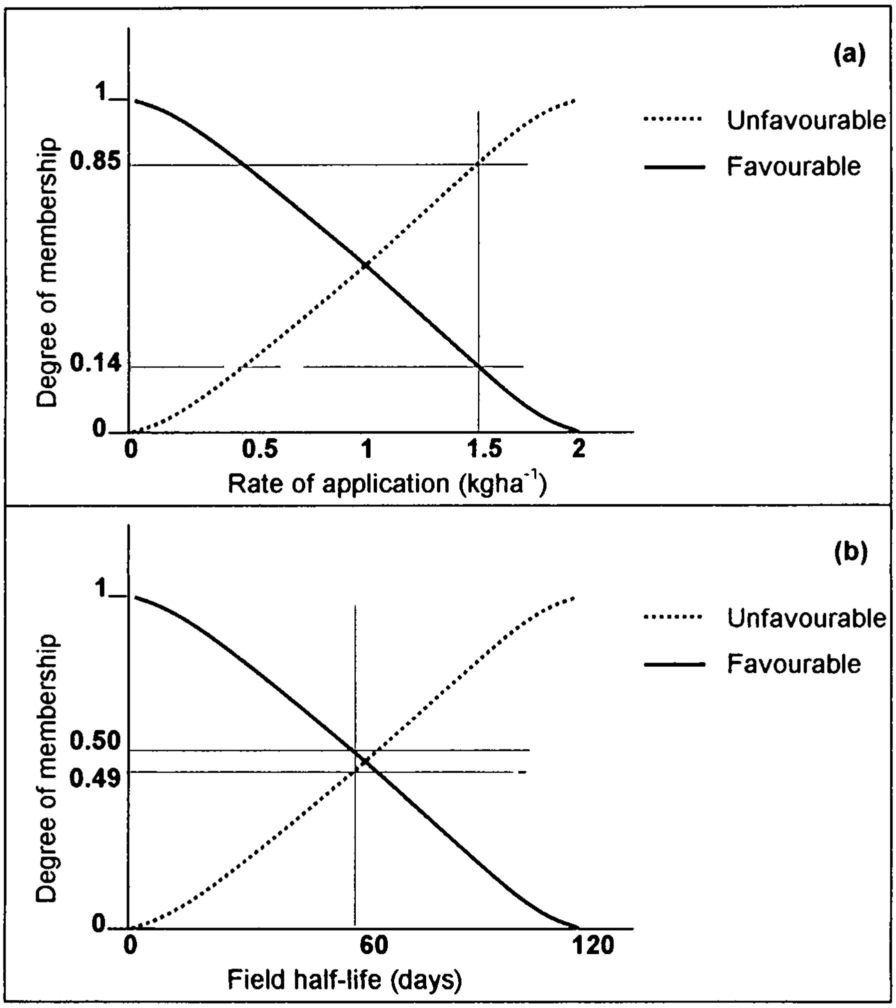


Figure 3-2. Membership to the fuzzy sets favourable and unfavourable for atrazine (a) rate of application and (b) field half-life

According to Sugeno's (1985) inference method, the truth value of a decision rule can be defined as the smallest of the truth values. The value for the final risk is calculated as the average of the conclusions of the decision rules, weighted by their truth according to Equation 3.1:

$$\text{Risk} = \frac{(0\times 0.147 + 0.5\times 0.147 + 0.5\times 0.506 + 1\times 0.494)}{(0.147 + 0.147 + 0.506 + 0.494)} = 0.634$$

This implies that the risk of possible contamination is 63.4 %.

3.3 STRUCTURE OF THE DECISION TOOL

For each of the tiers the following risk assessments can be performed:

- A groundwater risk assessment can be defined as the probability of an adverse effect or effects on the sustainability and/or quality of groundwater associated with measured or predicted hazards (for example chemical spills).
- A groundwater health risk assessment can be defined as a qualitative or quantitative process to characterise the probability of adverse health effects associated with measured or predicted levels of hazardous agents in groundwater. The health risk assessment is divided into a carcinogenic, a radiogenic, a non-carcinogenic and a microbial assessment.
- Ecological risks of interest differ qualitatively between different stresses, ecosystem types, and locations. A groundwater ecological risk assessment quantifies the impacts of groundwater quantity and quality on ecosystems. However, according to the National Water Act (Act No. 36, 1998) only aquatic ecosystems need to be considered. Therefore emphasis will be placed on these ecosystems.

Information from both the groundwater sustainability and contaminant risk assessments can be used as input data for health and ecological risk assessments.

Once the desired risk assessments have been completed, a cost-benefit-risk analysis can be used to aid in decision-making regarding the management and remediation of a groundwater resource. A cost-benefit-risk analysis is defined as a set of procedures used for defining, comparing and measuring benefits and costs, which originate from either an investment or the operation of a service. The cost-benefit-risk analysis is a flexible and adaptable method; however, the assessor should keep the suitability of a cost-benefit-risk analysis for different types of projects in mind before an attempt is made to perform the analysis.

The method used to determine a cost-benefit-risk analysis is similar to that documented by Rosen and LeGrand (1997). Monetary risk is defined as R = PC where P is the probability of failure and C represents the economical consequences associated with the failure expressed in monetary terms. To choose between the different alternatives an objective function is set up including the benefits, costs and risks of a project.

Since the early 1980's geohydrologists and engineers have developed a number of techniques for protecting groundwater. The government places such great emphasis on protection of water resources that a whole chapter of the National Water Act (Act No. 36, 1998) is dedicated to this topic. Protection is divided into two categories: measures to prevent failure and pollution of water resources and measures to remedy the effects of pollution of water resources.

On completion of the different aspects of the DT, a report including the input data and results of the risk assessments and cost-benefit-risk analysis will be generated. Depending on the user, prevention measures can be included. Unfortunately, no in-depth study has been completed for remediation options but the user will be able to do a search on various options. The results of the search can be included in the report.

The information obtained from the DT can be used for risk management. Risk management is defined as the process of identifying, evaluating, selecting and implementing actions to reduce risks.

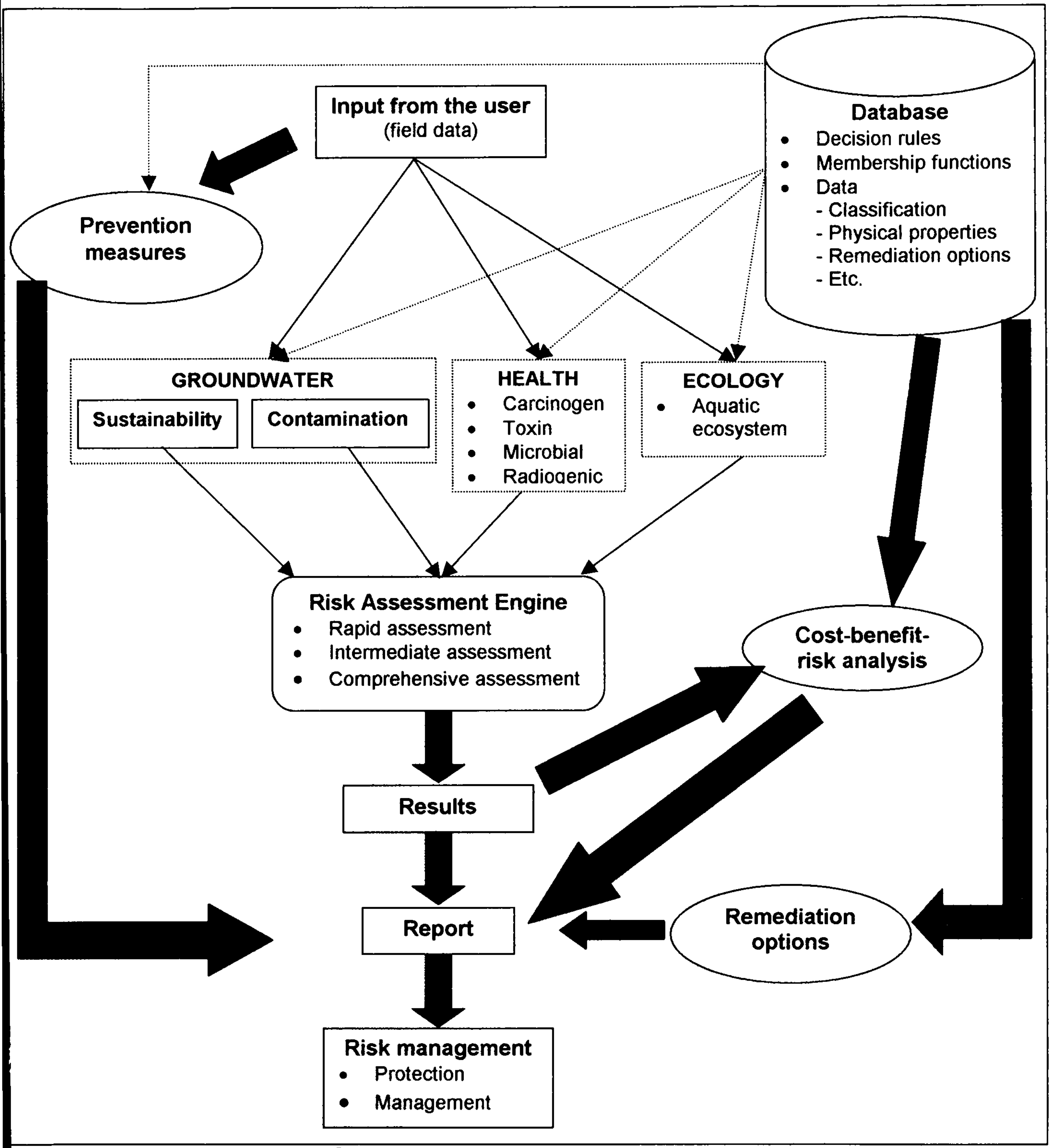


Figure 3-3. Simplified schematic representation of decision tool

Each of the components of the DT will be discussed in more detail in the following chapters.

3.4 DECISION TOOL SOFTWARE

The DT software was developed by SR Dennis using Borland C++ Builder Pro. The DT is linked to an MS Access Database in which all data, decision rules and membership function data are stored. The start-up screen for the DT is shown in Figure 3-4.

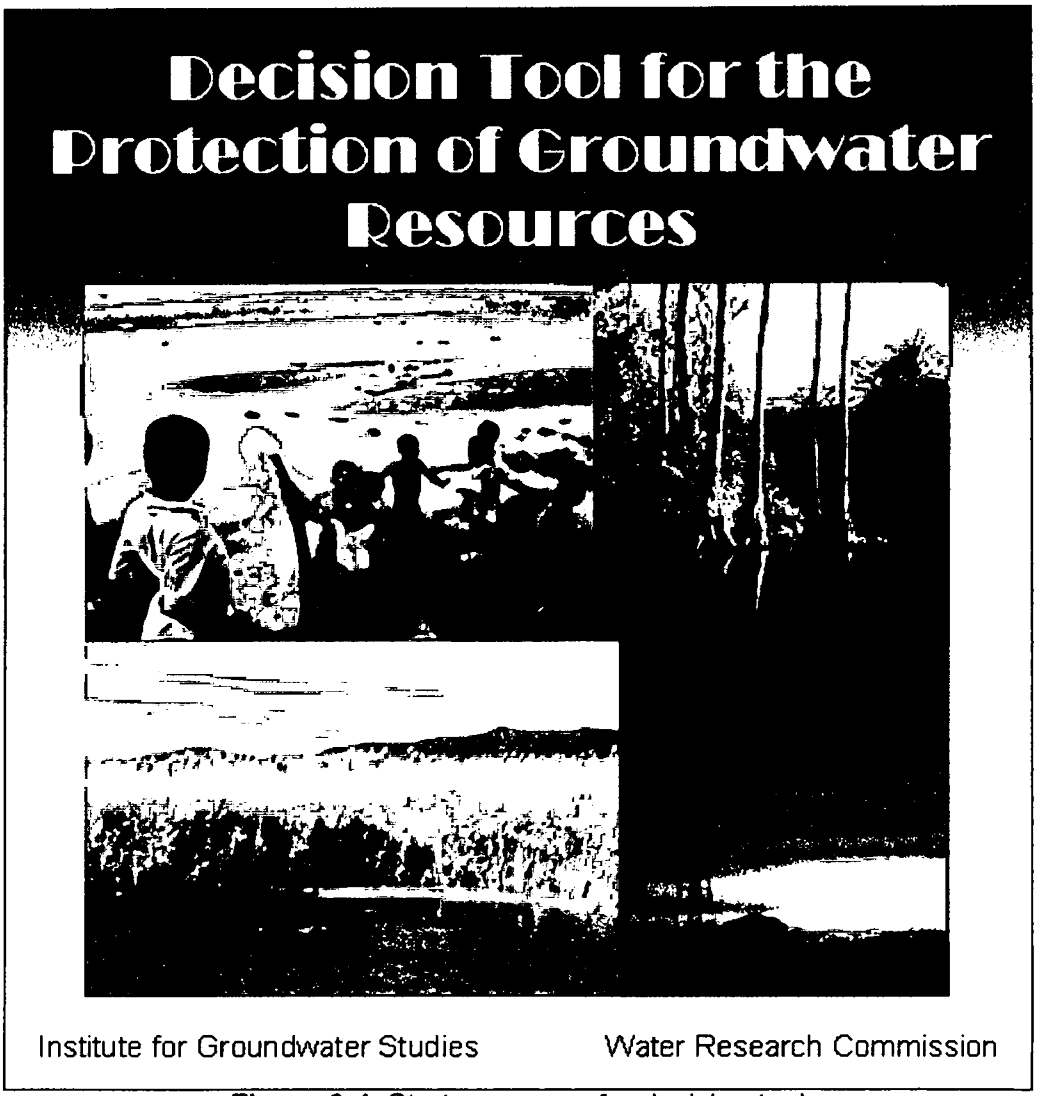
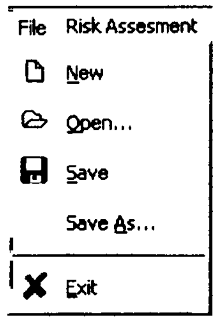
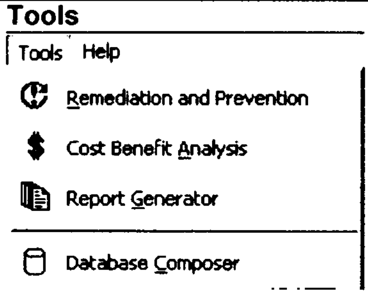
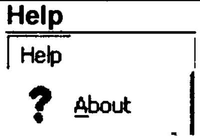


Figure 3-4. Start-up screen for decision tool

The functions on the main menu of the DT are summarised in Table 3.2.

Table 3.2: Functions on main menu of decision tool

Main menu	Function
File 	Contains usual software functions such as "new", "open", "save", "save as" and "exit". "Open", "save" and "save as" allow the user to call up an existing project file without having to start from the beginning every time.
Risk Assessment 	The risk assessment menu contains all risks assessments that can be performed by the DT. Each of the assessments is further divided into a rapid, intermediate and comprehensive assessment.
Tools 	Under the "tools" menu there is the remediation and prevention option, the cost-benefit-risk analysis and the report generator that takes all data into account. The database composer gives the user access to the database which contains decision rules, membership functions, data etc.
Help 	The help function provides information concerning the people and institutions involved in developing the DT. However, there are other help functions available in various sections of the DT.

Once the start-up screen has disappeared, the main screen of the DT will appear (Figure 3-5). Here the user can decide which risk assessment he/she would like to do. By default the rapid assessment for sustainability appears. However the user can move to any of the other assessments by selecting the respective tab. Each of the assessments together with the cost-benefit-risk analysis, prevention and remediation, and the generation of reports will be discussed in more detail in the examples in Chapters 4 – 9. The only aspect of the DT still to be mentioned here is the database. The only way to enter the database is by means of a password. Once the access code has been entered the main database screen appears. The structure of the database is similar to Windows Explorer. For example, consider the sustainability risk assessment. All information needed for this risk assessment is stored under sustainability (Figure 3-6). Similarly information for the other risk assessments is stored in the database and can be accessed and changed here.

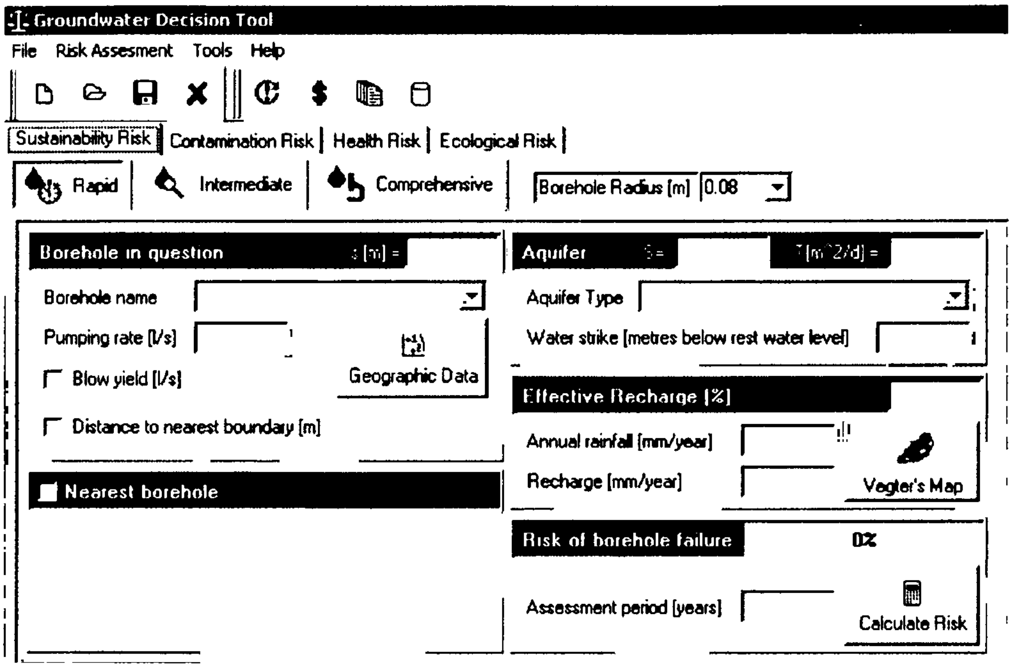
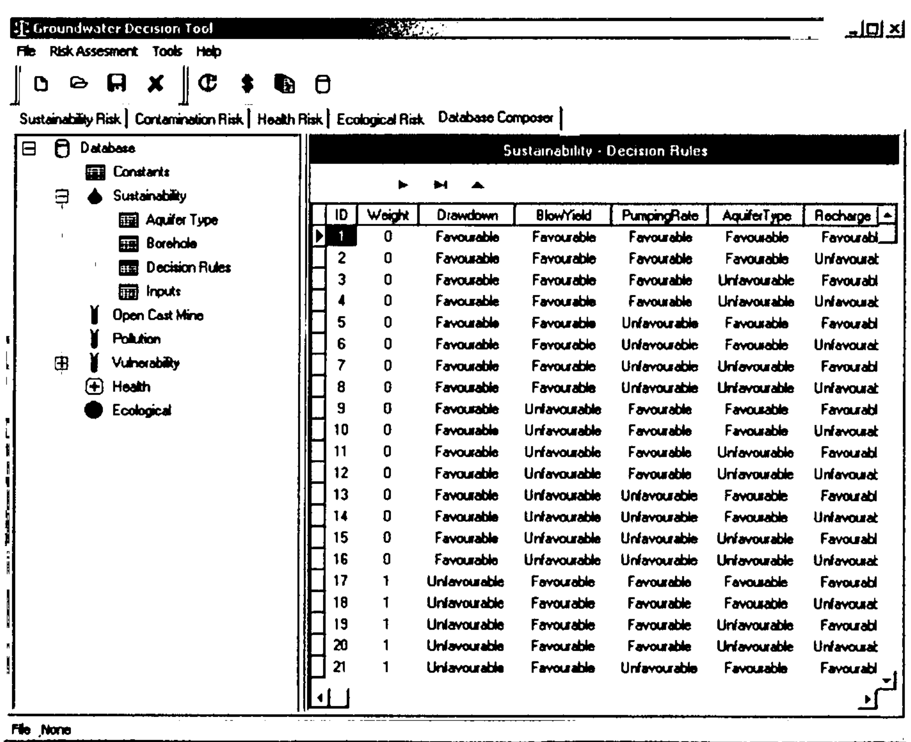


Figure 3-5. Main screen of the decision tool



ID	Weight	Drawdown	BlowYield	PumpingRate	AquiferType	Recharge
1	0	Favourable	Favourable	Favourable	Favourable	Favourabl
2	0	Favourable	Favourable	Favourable	Favourable	Unfavourat
3	0	Favourable	Favourable	Favourable	Unfavourable	Favourabl
4	0	Favourable	Favourable	Favourable	Unfavourable	Unfavourat
5	0	Favourable	Favourable	Unfavourable	Favourable	Favourabl
6	0	Favourable	Favourable	Unfavourable	Favourable	Unfavourat
7	0	Favourable	Favourable	Unfavourable	Unfavourable	Favourabl
8	0	Favourable	Favourable	Unfavourable	Unfavourable	Unfavourat
9	0	Favourable	Unfavourable	Favourable	Favourable	Favourabl
10	0	Favourable	Unfavourable	Favourable	Favourable	Unfavourat
11	0	Favourable	Unfavourable	Favourable	Unfavourable	Favourabl
12	0	Favourable	Unfavourable	Favourable	Unfavourable	Unfavourat
13	0	Favourable	Unfavourable	Unfavourable	Favourable	Favourabl
14	0	Favourable	Unfavourable	Unfavourable	Favourable	Unfavourat
15	0	Favourable	Unfavourable	Unfavourable	Unfavourable	Favourabl
16	0	Favourable	Unfavourable	Unfavourable	Unfavourable	Unfavourat
17	1	Unfavourable	Favourable	Favourable	Favourable	Favourabl
18	1	Unfavourable	Favourable	Favourable	Favourable	Unfavourat
19	1	Unfavourable	Favourable	Favourable	Unfavourable	Favourabl
20	1	Unfavourable	Favourable	Favourable	Unfavourable	Unfavourat
21	1	Unfavourable	Favourable	Unfavourable	Favourable	Favourabl

Figure 3-6. Database of the decision tool

3.5 INTERPRETATION OF RISKS GENERATED BY THE DECISION TOOL

Risk assessment is a way of thinking about or analysing a situation, and as such it is a combination of science and judgement. Risk is a combination of two factors: (1) the chance that an adverse event will occur and (2) the consequences of that event. In this thesis there are four different risk assessments namely:

- Risk of a borehole or groundwater resource failing.
- Risk of a groundwater resource being contaminated.
- Risk of poor groundwater quality affecting human health.
- Risk of an aquatic ecosystem being affected by changes in groundwater quantity and/or quality.

Risk values are stated as a percentage. The higher the percentage the greater the potential of negative impacts. The highest risk obtainable is 99% indicating that under the conditions stipulated in the respective risk assessment there chances of the agent (be it groundwater, human health or an aquatic ecosystem) being impacted are extremely high.

It is the manager's decision as to whether a risk is acceptable or not. For example a manager might decide a 25% chance of a borehole failing is acceptable, however a 25% chance of a person becoming seriously ill when drinking contaminated groundwater is not acceptable.

The calculated risks are dependent on the confidence in data and method used to calculate the risks, therefore it is important for the manager to understand the fuzzy logic methodology and the associated membership functions.

Chapter 4

Groundwater Sustainable Risk Assessment

4.1 PREAMBLE

Braune (2000) stated: *Groundwater is particularly vulnerable to poor management. This is because of its 'invisible' nature, the often delay before over-exploitation manifests itself and the limited self-purification. Once groundwater becomes polluted, it is difficult, if not impossible, to rehabilitate. Unfortunately groundwater resources, both in quality and yield, are put at risk by a wide range of human activities. These should be managed to ensure the sustainable utilisation of the resource. . . . To avoid unnecessary risks to groundwater resources, requires knowledge-based management. However, obtaining such knowledge in the case of groundwater is an incremental process necessitating a precautionary approach to all groundwater management decisions. Strategies and actions should be pro-active, planned and preventative, wherever possible, rather than reactive.*

As a result, pro-active methodologies must therefore be developed in order to ensure the protection of this valuable resource. One such methodology uses risk assessments based on fuzzy logic to determine the potential failure of a groundwater resource, taking into account both the quantity and quality of the resource. The methodologies capture the knowledge of experts in the field of groundwater sustainability and contamination. This chapter will focus on the groundwater sustainablity or quantity risk assessment. Chapter 5 will deal with quality or contamination risk assessment.

4.2 GROUNDWATER SUSTAINABLE RISK ASSESSMENT

4.2.1 General

There are many definitions for groundwater sustainability. Sharp (1998), for example, defined the sustainable yield of groundwater as the minimisation of potential negative effects on an aquifer so that it can be utilised at an acceptable range of levels for a very long period of time. Merrick (2000) stated that sustainable yield is that proportion of the long-term annual recharge, which can be abstracted each year without causing unacceptable impacts on groundwater users or the environment. Van Tonder's (2001) definition of sustainable yield is that it is the safe amount of water that can be abstracted from a borehole for a long time (usually 1 or 2 years), without the water level reaching the position of the pump or the main water strike.

An increasing number of boreholes in Southern Africa have dried up during the past years in spite of comparable constant hydrologic conditions. A new investigation of reliable estimates for the sustainable yield of the boreholes was therefore required. Overestimation of the borehole yield was due to the application of improper extrapolation of drawdown curves, which ignored barrier boundaries and neglected parameter uncertainties arising from the imperfect knowledge of the effective aquifer properties (Van Tonder *et al.*, 1999).

A groundwater quantity risk assessment has therefore been designed to determine the risks of failure when abstracting from an aquifer. The author felt it important to consider not only recharge, but also other important factors to ensure that the water level does not reach the main water strike or pump position. These factors include:

- Blow yield, which can be used to determine an estimate for the sustainable borehole yield.
- Recharge, which is an important factor according to the definitions of sustainable yield.
- Water strike/depth of main fracture which determines the amount of drawdown possible in a borehole. According to Van Tonder's (2001) definition of sustainable yield, it is important not to abstract a quantity of water such that the water level reaches the water strike or pump.
- The drawdown in the borehole under investigation must not reach the main water strike. This drawdown is calculated taking into account the influence of other abstraction boreholes and boundaries.
- The aquifer type will determine the amount of water that can be released from storage.
- The period for which the users would like to abstract is important. Calculations show (Van Tonder and Dennis, 2000), the longer the period of abstraction, the larger and deeper the cone of influence.

- Slug and pumping tests are used to determine information concerning aquifer parameters. In addition borehole logs and pumping test data can indicate the position of fractures.

The methodology to determine the risk of borehole or aquifer failure due to over abstraction is summarised in Figure 4-1.

4.2.2 Data Requirements

One of the major differences between the three tiers of assessments is the quality of data used for each assessment. This can be seen from the data requirements listed in Table 4.1. Maps and databases (containing data from literature) are used in the rapid assessment. Data from at least one field investigation is included in the intermediate assessment thereby improving confidence in the results. The comprehensive assessment requires a full set of field data to attach a medium to high confidence to the results.

4.2.3 Assumptions and Limitations

The assumptions and limitations for the various assessments differ and will therefore be discussed separately.

Rapid Assessment

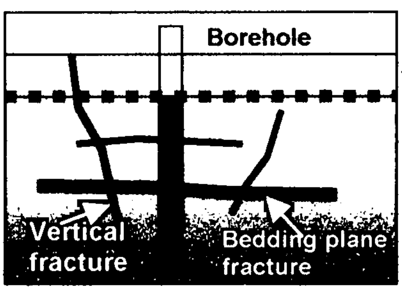
- Only the influence of the closest no-flow boundary and abstraction borehole is taken into account.
- Literature, maps, rules of thumb and simple calculations are used to determine the membership functions and decision rules.
- The Cooper-Jacob method is used to determine the drawdown at the borehole under investigation. It is also used to determine the drawdown at the borehole under investigation as a result of the closest abstraction borehole.
- When determining the drawdown in a borehole under investigation, the actual radius of the borehole is used and not the effective radius.
- The risk assessment can only be conducted on one borehole.

Groundwater sustainable risk assessment

Problem formulation

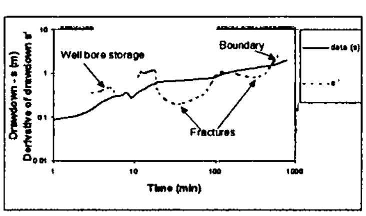
Hazard identification establishes whether abstraction at a given rate will negatively impact the aquifer.

Questions to be asked: What is the problem? Why is it a problem? Are the effects likely to appear in the near future, or in future generations? How urgent is the need for action?



Analysis

Establishes the tendency or likelihood for abstraction to have negative effects on the groundwater levels. Establishes risks of potential impacts taking into account the properties of the aquifer.



Risk characterisation

Provides an indication of the incidence of possible impacts taking into account properties of the aquifer and the abstraction boreholes. Risk characterisation should include information that is useful to both stakeholders and risk managers. *Questions to be asked:* What is the nature and likelihood of the risk? How severe are the anticipated adverse effects? Are the effects reversible? What scientific evidence supports the conclusions about the risk? How strong is the evidence? What is uncertain about the nature or magnitude of the risk?

Figure 4-1. Summary of methodology for sustainable risk assessment

Table 4.1: Data required for sustainable risk assessment and potential data sources

Data required	Potential data sources		
	Rapid	**Intermediate**	**Comprehensive**
Blow yield	User/guesstimated by DT	User/estimated by DT	User/estimated by DT
Recharge • Recharge • Rainfall • Chloride values in groundwater and rainfall • Water levels	 User/recharge map[1] Weather bureau/user -	 User/recharge map[1] OR Weather bureau/user Laboratory analyses/database	 User OR Weather bureau/user Laboratory analyses OR Field data
Other abstraction boreholes[2] • Distance between investigated borehole & other abstraction boreholes • Positions of boreholes • Abstraction rates	 User OR User User	 User OR User User	 User OR User User

Aquifer information
• Type/storativity
 	
• Transmissivity
  o Slug test data
  o Pumping test
	
	User[3] (drop down menu in DT)
	User
	-
	
	-
		
		User[3] (drop down menu in DT)
		
		Field data
		OR
		Field data
			
			User[3] (drop down menu in DT)
			-
			-
			
			Field data

Water strike/fracture	User	User/pumping test data/borehole log	User/pumping test data/borehole log
Aquifer boundaries • Distance to closest no-flow boundary • Positions of aquifer no flow boundaries	 User OR User (*.bnd file) can be determined from field investigations, geological or topographic maps	 - User (*.bnd file) can be determined from field investigations, geological or topographic maps	 - User (*.bnd file) can be determined from field investigations, geological or topographic maps
Period for which the borehole under investigation is to be pumped.	User	User	User

[1]Map included in Decision Tool (See Appendix A, Section A1).
[2]Only closest abstraction borehole to borehole under consideration taken into account for the rapid assessment.
[3]Data used in the drop down menu is documented in Appendix A, Section A2.
- Data not needed for assessment.
GENERAL NOTE: Manual override of calculated values is possible.

Intermediate Assessment

- Five different boundary configurations are taken into account, namely:
  - No boundary
  - Single barrier boundary
  - Two barrier boundaries intersecting at 90°
  - Two parallel boundaries
  - Closed square boundaries

  Refer to Appendix A (Section A3) for more information concerning the boundary conditions.
- The Cooper-Jacob method is used to determine the drawdown at the borehole under investigation. It is also used to determine the drawdown at the borehole under investigation as a result of other abstraction boreholes in the area.
- When determining the drawdown in a borehole, the actual radius of the borehole is used and not the effective radius.
- The risk assessment can be conducted on numerous boreholes, but the highest calculated risk will be taken as the final risk of the wellfield.

Comprehensive Assessment

- The five different types of boundaries listed under the intermediate assessment are taken into account.
- The influence of a fracture is included using the Barker's GRF-model and the non-integer flow dimension (refer to Chapter 2).
- When determining the drawdown in the borehole under consideration, the actual radius of the borehole is used and not the effective radius.
- The risk assessment can be conducted on numerous boreholes, but the highest calculated risk will be taken as the final risk of the wellfield.
- The user must use the Hurst method to determine n and the GRF-model to determine the drawdowns. This allows the user to take the fracture nature of the aquifer into account. If working with a porous aquifer n should be 2 and the GRF-model will give the same results as the Theis model. If, however, the user would prefer using the Cooper-Jacob method, then the intermediate assessment can be used.

4.2.4 Methodology

The methodologies (Table 4.2) differ slightly when calculating the data required for the membership functions and therefore these calculations will be discussed separately for each of the assessments. The calculations vary from elementary calculations for the rapid assessment to complex sophisticated calculations for the comprehensive assessment.

Table 4.2: Methodologies for calculating a sustainable assessment

Data required for various calculations	Calculations		
	Rapid assessment	**Intermediate assessment**	**Comprehensive assessment**
Blow yield: A common rule-of-thumb in groundwater circles indicates that the rate at which a borehole can be pumped is approximately 20% of the blow yield for 24 hr/day or 60% for 8 hr/d. Therefore, blow yield can be used as a first estimate of the sustainable yield of a borehole.	If the blow yield of the borehole is not known, it can be estimated using the following equation: blow yield = 1.7 x current pumping rate.	If the blow yield of the borehole is not known, it can be estimated using the following equation: blow yield = 1.7 x current pumping rate.	If the blow yield of the borehole is not known, it can be estimated using the following equation: blow yield = 1.7 x current pumping rate.
Blow yield: Is used to determine transmissivity for the rapid assessment. *Slug test/pumping test data:* The data from these tests are used to calculate the transmissivity/hydraulic conductivity values in the intermediate and comprehensive assessments.	The blow yield is also used to determine the transmissivity of the aquifer using the following rule-of-thumb: T (m/d) = 10 x 0.6 x blow yield (L/s).	Slug test data are used to calculate the yield of a borehole Q (L/h) = $117155.08t^{-0.824}$ Where t is the recession time of the slug test in seconds (Vivier *et al.*, 1995), the transmissivity is then calculated using the rule-of-thumb: T (m/d) = 10 x Q (L/s) OR Use the data of one pumping test to obtain a value for T using the Cooper-Jacob method (Kruseman and De Ridder, 1991) OR Logan's formula (Misstear, 1991) can be used to determine the transmissivity: $T \approx 1.22 \frac{Q}{s}$ where Q is the discharge rate and s is the associated drawdown after a long period of time.	If in a fractured aquifer pumping test data are used to determine the non-integer flow dimension n using the Hurst method (See Chapter 2), this n is then substituted into GRF-model and, using curve fitting, a K and S value for the fracture aquifer can be determined (refer to Chapter 2). If in porous aquifer n ≈ 2 and the GRF-model will collapse to the Theis equation.
Recharge: Annual rainfall for the rapid assessment and intermediate assessment. Chloride values in rainfall and groundwater for the intermediate and comprehensive assessment. Time series groundwater levels and rainfall data are needed for the comprehensive assessment.	Recharge is calculated directly from Vegter's recharge map (Vegter, 1995).	Recharge is calculated directly from Vegter's recharge map (Vegter, 1995). OR Recharge is calculated using the chloride method (Appendix A, Section A4).	Recharge is calculated using the chloride method (Appendix A, Section A4). OR Recharge is calculated using the EARTH method (Appendix A, Section A4).

Table 4.2 continued

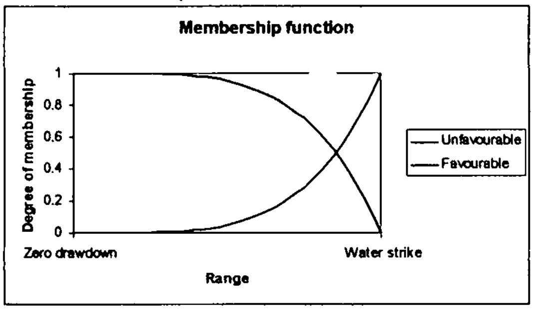
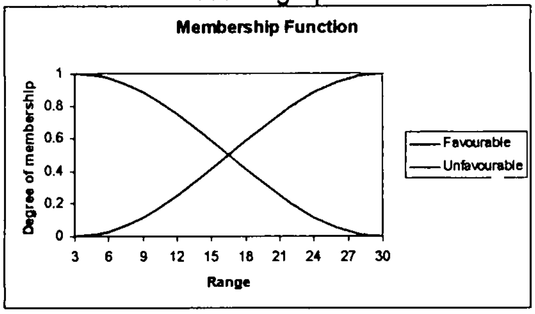
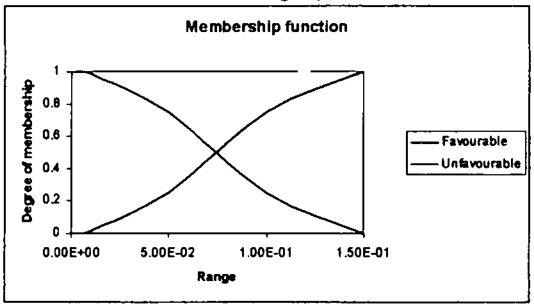
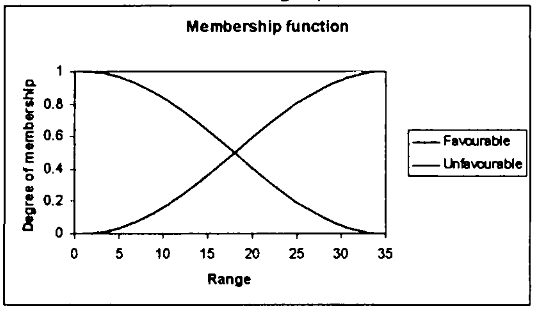
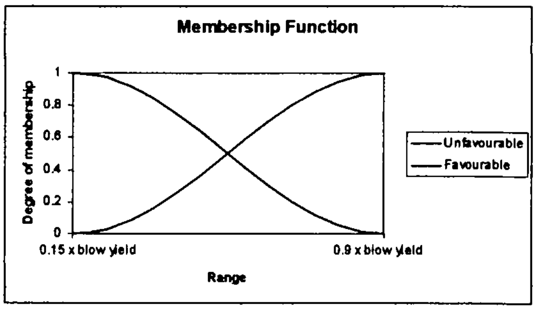
Period (t) for which pumping is going to take place, abstraction rate in borehole under investigation (Q), positions of other abstraction boreholes and abstraction rates, aquifer type and boundary conditions: This information is used to determine the drawdown in the borehole under consideration taking into account other abstraction boreholes and aquifer boundaries. For the rapid assessment only the distances to the closest no-flow boundary and abstraction borehole need to be entered.	The drawdown in the borehole under consideration is determined using the Cooper-Jacob method (Kruseman and De Ridder, 1991) $s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2S}$ where r = radius of the borehole and T is determined from rule-of-thumb. S is determined from the aquifer type or directly from the user. The drawdown resulting from the closest abstracting borehole is determined using the same equation except Q is the abstraction rate in the other abstracting borehole, and r is the distance between the closest abstracting borehole and the borehole under investigation. The drawdown as a result of the closest boundary is calculated	The drawdown in the borehole under consideration is determined using the Cooper-Jacob method (Kruseman and De Ridder, 1991) $s = \frac{2.3Q}{4\pi T}\log\frac{2.25Tt}{r^2S}$ where r = radius of the borehole and T is determined from slug tests or pumping tests. S is determined from the aquifer type or directly from the user. The drawdown in abstraction borehole i is determined as $s_i = \frac{2.3Q_i}{4\pi T}\log\frac{2.25Tt}{r_i^2S}$ where Q_i is the abstraction rate in borehole i and r_i is the distance between borehole i and the borehole under investigation. The drawdown in the borehole under investigation which results from the aquifer boundaries is calculated as in Appendix A, Section A3. The total drawdown in the borehole under investigation is then $s_{total} = s_b + \sum s_i + s$ where s is the drawdown in the borehole not taking into account other factors, s_b = drawdown in borehole as a result of the boundaries and $\sum s_i$ = the drawdown in the borehole under investigation as a result of other abstraction boreholes in the area.	The drawdown in the borehole under consideration is determined using the GRF-model (see Chapter 2) $s = \frac{Q}{4\pi^{1-N}K_f b^{3-n}N}\left[\left(\frac{4K_f t}{S_{sf}}\right)^N - \Gamma(1-N)r^{2N}\right]$ Where K_f, S_{sf}, b and r are determined by means of curve fitting. N = 1-n/2, n is determined by means of the Hurst method. The drawdown in abstraction borehole i is determined as $s_i = \frac{Q_i}{4\pi^{1-N_i}K_{f_i} b_i^{3-n_i}N_i} x \left[\left(\frac{4K_{f_i} t}{S_{sf_i}}\right)^{N_i} \Gamma(1-N_i)r_i^{2N_i}\right]$ Where Q_i is the abstraction rate in borehole i, K_{fi}, S_{sfi}, b_i and r_i are determined by means of curve fitting of pumping test data from borehole i. N_i = 1-n_i/2 and n_i is determined by using the Hurst method, calculated from pumping test data from borehole i. The total drawdown in the borehole under investigation is then $s_{total} = s_b + \sum s_i + s$ where s is the drawdown in the borehole not taking into account other factors, s_b

Table 4.2 continued

	as in Appendix A, Section A3, *Single barrier boundary*. The total drawdown in the borehole under investigation is then $s_{total} = s_b + s_c + s$ where s is the drawdown in the borehole not taking into account other factors, s_b = drawdown in borehole as a result of the boundary and s_c is the drawdown in the borehole under investigation as a result of the closest abstraction borehole.		= drawdown in borehole as a result of the boundaries and $\sum s_i$ = the drawdown in the borehole under investigation as a result of other abstraction boreholes in the area. *It is important to note that the boundary calculations are in terms of transmissivity and storativity and therefore K_f and S_{sf} must be multiplied with the thickness of the aquifer.*
Pumping rate: The user enters the desired pumping rate of the borehole under investigation and the risk of failure is determined for the entered value.			

The membership functions together with their upper and lower limits have been set by experts (G van Tonder from the Institute for Groundwater Studies and R Murray from the CSIR) in the groundwater field and are listed in Table 4.3.

Table 4.3: Membership functions

<table>
<tr><th colspan="4">Membership functions[1]</th></tr>
<tr><td colspan="2">Drawdown
The drawdown membership function is a power function.

</td>
<td colspan="2">Blow yield
The blow yield membership function is a cosine graph.

</td></tr>
<tr><td>Unfavourable limit</td><td>Favourable limit</td><td>Unfavourable limit</td><td>Favourable limit</td></tr>
<tr><td>Water strike/main fracture</td><td>No drawdown</td><td>≤ 3 L/s</td><td>≥ 30 L/s</td></tr>
<tr><td colspan="2">Aquifer type (storativity)
The storativity membership function is a cosine graph

</td>
<td colspan="2">Recharge
The recharge membership function is a cosine graph

</td></tr>
<tr><td>Unfavourable limit</td><td>Favourable limit</td><td>Unfavourable limit</td><td>Favourable limit</td></tr>
<tr><td>1×10^{-5}</td><td>0.15</td><td>≤ 1 %</td><td>≥ 35 %</td></tr>
<tr><td colspan="2">Pumping rate
The pumping rate membership function is a cosine graph.</td>
<td colspan="2">
</td></tr>
<tr><td colspan="2">Unfavourable limit
0.9 x blow yield</td><td colspan="2">Favourable limit
0.15 x blow yield</td></tr>
</table>

[1]The equations for the membership functions are documented in Appendix A, Section A5

The decision rules for all assessments and associated conclusions have been set by G van Tonder. These rules are listed in Appendix E, Section E1. It is important to note that the decision rules and corresponding conclusions have been set up so that the drawdown carries the most weight.

4.2.5 Example

4.2.5.1 General information

As mentioned in Chapter 2, the Campus test site is located on the grounds of the University of the Free State, South Africa, and covers an area of approximately 180x192 m^2. The aquifer is intersected by thirty percussion and seven core-boreholes (Figure 4-2).

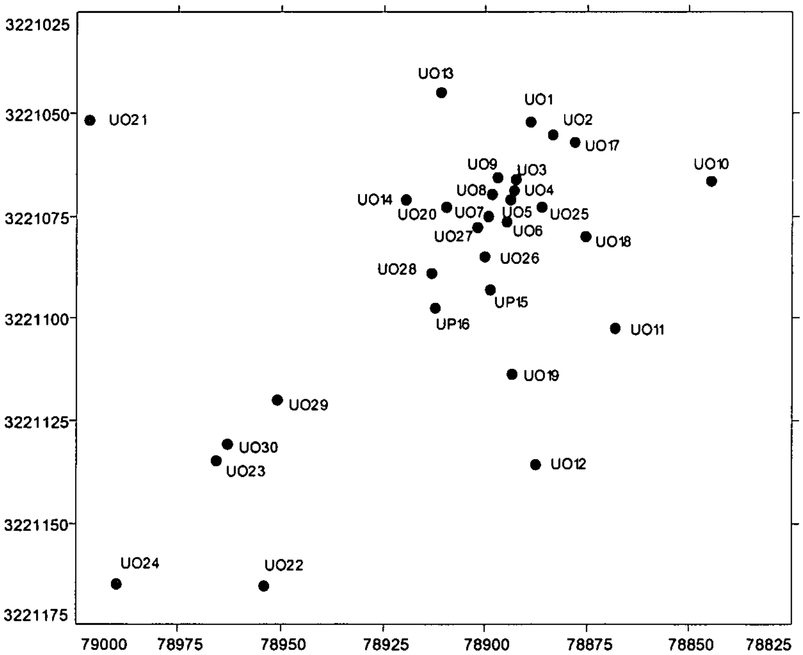


Figure 4-2. The Campus Test Site

The thickness of the aquifer on site is approximately 50m. The aquifer is situated in the Karoo Sequence and the geology consists of sandstone, mudstone and shale deposited under fluvial conditions. Core samples indicate parallel horizontal fractures, the most significant of which is at a depth of 21 m. In more weathered sections of the aquifer, diagonal fractures intersect the bedding plane fractures. The sandstone containing the most horizontal fractures also forms the main water carrying formation. In this analysis the risk of borehole UO5 failing will be determined.

4.2.5.2 Rapid risk assessment

The input values for the rapid assessment are summarised in Table 4.4 and are shown in Figure 4-3. The risk is then determined by selecting "calculate risk".

Table 4.4: Input data for rapid risk assessment

Input	Value
Borehole name	UO5
Pumping rate (L/s)	0.5
Distance to nearest boundary	877.5
Aquifer type	Karoo fractured rock
Water strike (m)	10
Annual rainfall (mm/year)	550
Recharge (mm/year)	Determined by clicking on Vegter's Map
Assessment period (years)	1

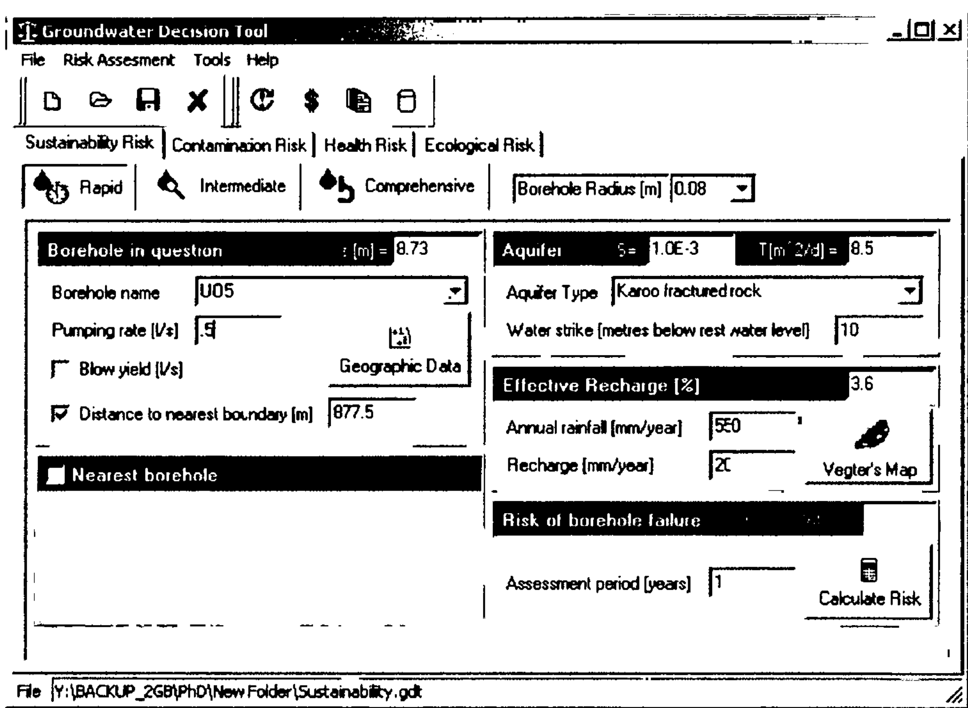


Figure 4-3. Rapid assessment screen

The user must note that if the distance to the closest boundary has not been calculated, then the boundary and borehole coordinates can be imported by selecting "geographic data" and the DT will calculate the distance for the user. The risk was calculated for various pumping rates over a period of 1 and 2 years respectively. The results are shown in Figure 4-4.

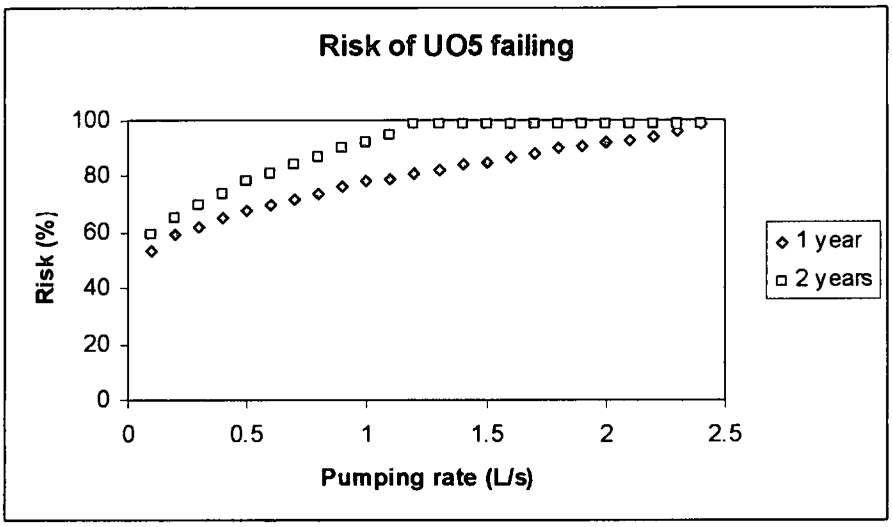


Figure 4-4. Risk of borehole UO5 failing (rapid assessment)

From extensive field investigations it has been proved that UO5 can be pumped for 6 months at 0.33 L/s without failing.

4.2.5.3 Intermediate risk assessment

The data required for the intermediate assessment is summarised in Table 4.5.

Table 4.5: Input data for the intermediate risk assessment

Input	Value
Borehole name	UO5
Borehole coordinates	X = 78893.61 Y = 21071.02
Pumping rate (L/s)	0.5
Boundary type - a - b	Perpendicular 877.5 1755
Aquifer type	Karoo fractured rock
Water strike (m)	10
Annual rainfall (mm/year) Chloride in rainfall (mg/L) Chloride in groundwater (mg/L)	550 1.1 39
Assessment period (years)	1
Pumping test data (to be analysed using the Cooper-Jacob method)	See Appendix A, Section A6 for imported pumping test data

The input screens for the intermediate assessment are shown in Figure 4-5.

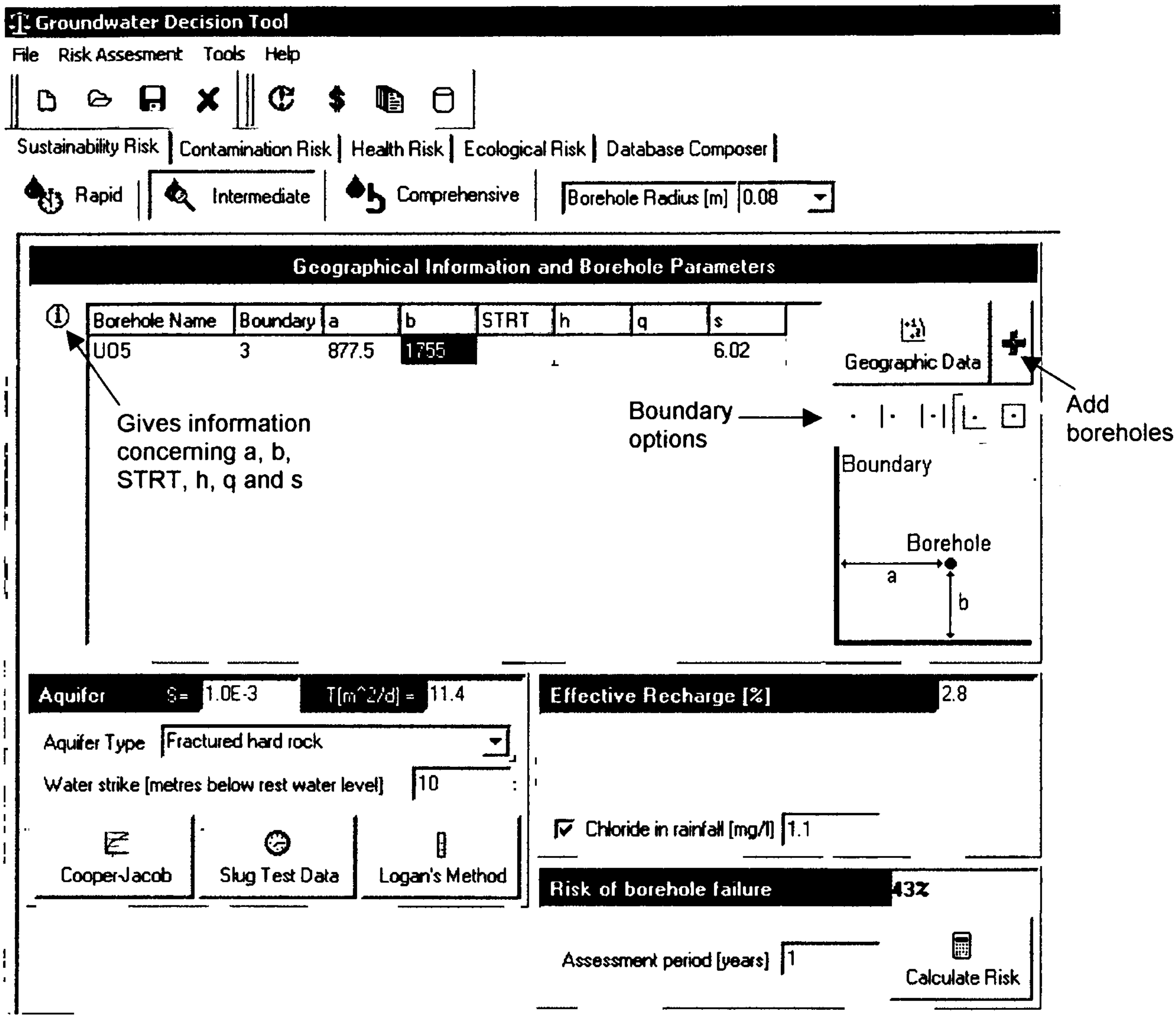


Figure 4-5(a). Main screen of intermediate sustainable assessment

When selecting "Cooper-Jacob", the following screen will appear (Figure 4-5(b)).

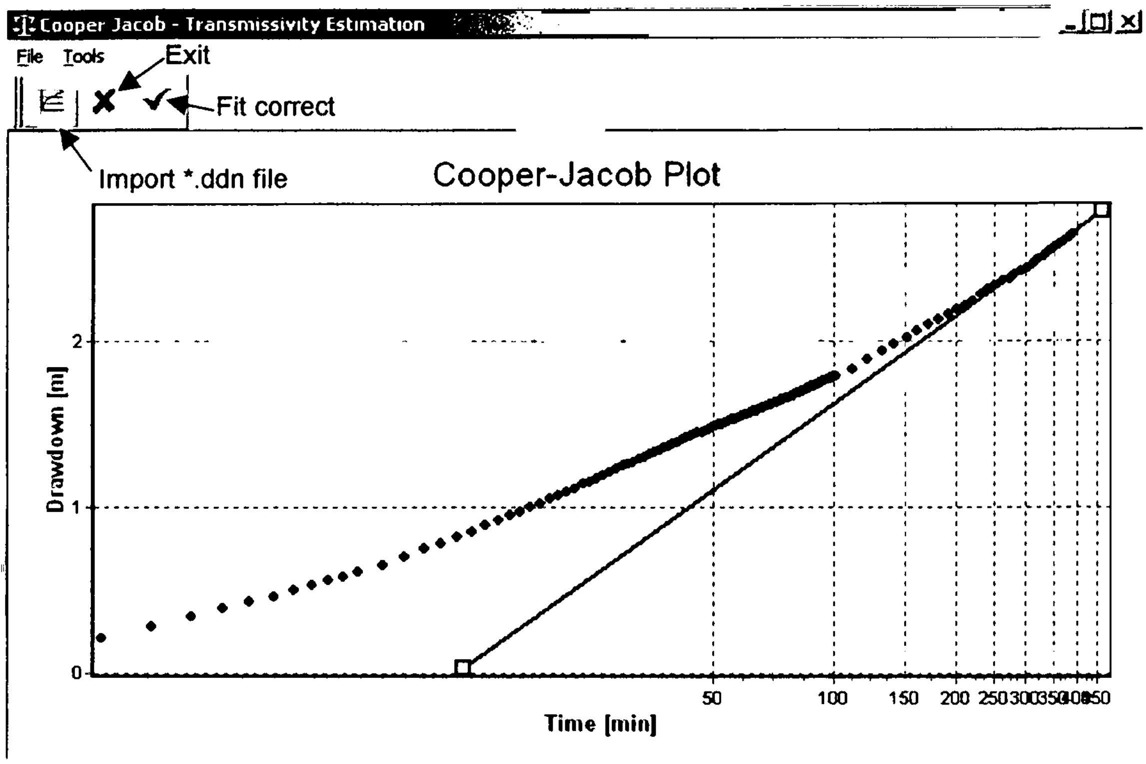


Figure 4-5(b). Screen to fit pumping test data using the Cooper-Jacob method

When selecting "Geographic Data", the following screen appears (Figure 4-5(c)).

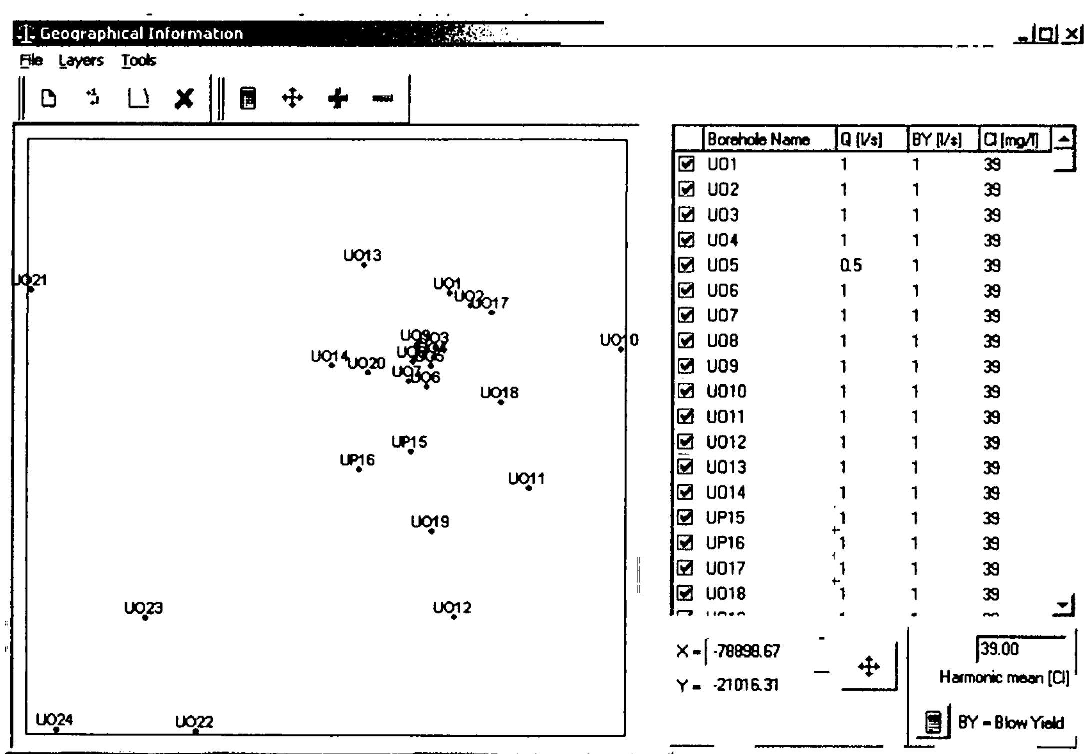


Figure 4-5(c). Input screen for geographical data

All the boreholes have been checked in Figure 4-5(c) to give the user an idea of software capabilities, and that more than one borehole can be assessed at a time. However, in this example only borehole UO5 is under consideration.

Every icon on the toolbar inclues hints to help the user. In Figure 4-5(c) the icons on the toolbar from left to right are: "new", "import boreholes", "import boundaries", "exit", "calculate blow yield", "fit to screen", "add borehole" and "delete borehole". The icons are repeated under the "file" and "tools" menu's. Under the "layers" menu the user can select or deselect the following: "text", "boundaries "and "radii of influence".

The format of the geographical data files (boreholes and boundaries) is documented in Appendix A, Section A7.

The risk of UO5 failing was calculated over a period of 1 and 2 years for various pumping rates (Figure 4-6).

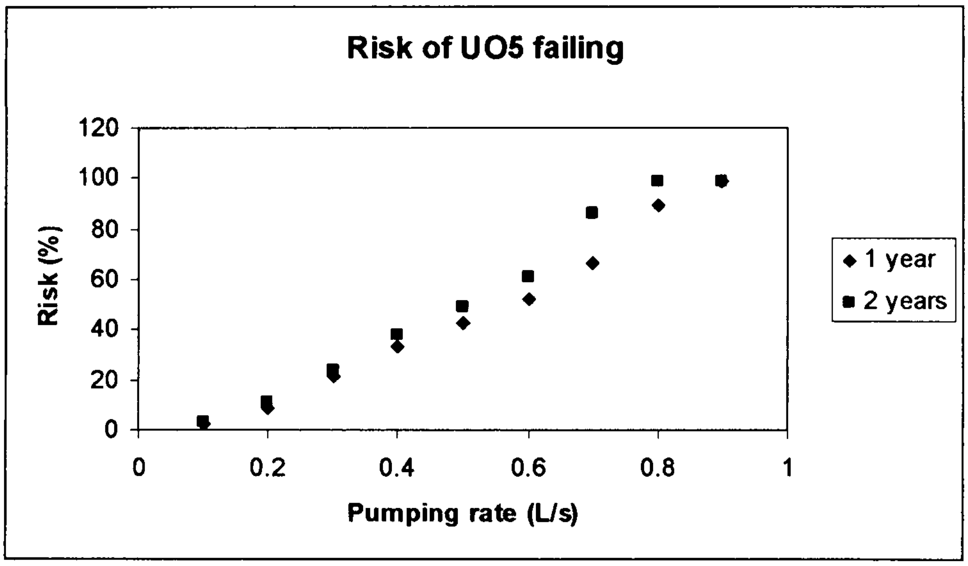


Figure 4-6. Risk of borehole UO5 failing (intermediate assessment)

4.2.5.4 Comprehensive risk assessment

The data required for the comprehensive assessment is summarised in Table 4.6.

Table 4.6: Input data for the comprehensive risk assessment

Input	Value
Borehole name	UO5
Borehole coordinates	Imported from *.bhl file. See Appendix A, Section A7
Pumping rate (L/s)	0.5
Boundary type - a - b	Perpendicular 877.5 1755
Aquifer type	Karoo fractured rock
Water strike (m)	10
Annual rainfall (mm/year) Chloride in rainfall (mg/L) Chloride in groundwater (mg/L)	550 1.1 39
Assessment period (years)	1
Pumping test data (to be analysed using the Hurst method and GRF-model)	See Appendix A, Section A6 for imported pumping test data

The input screens for the assessment are shown in Figure 4-7.

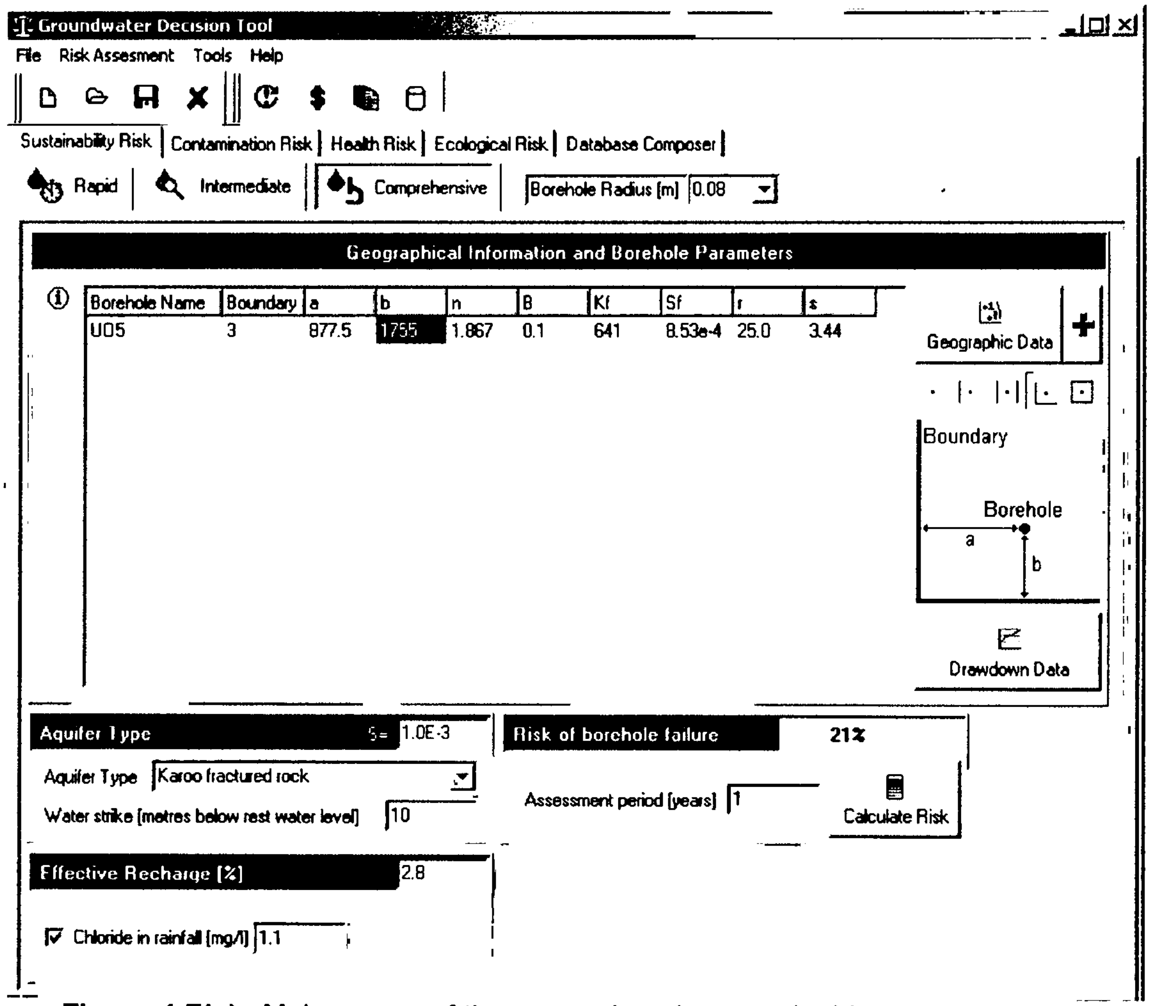


Figure 4-7(a). Main screen of the comprehensive sustainable assessment

When selecting "drawdown data" the following screen (Figure 4-7(b)) appears:

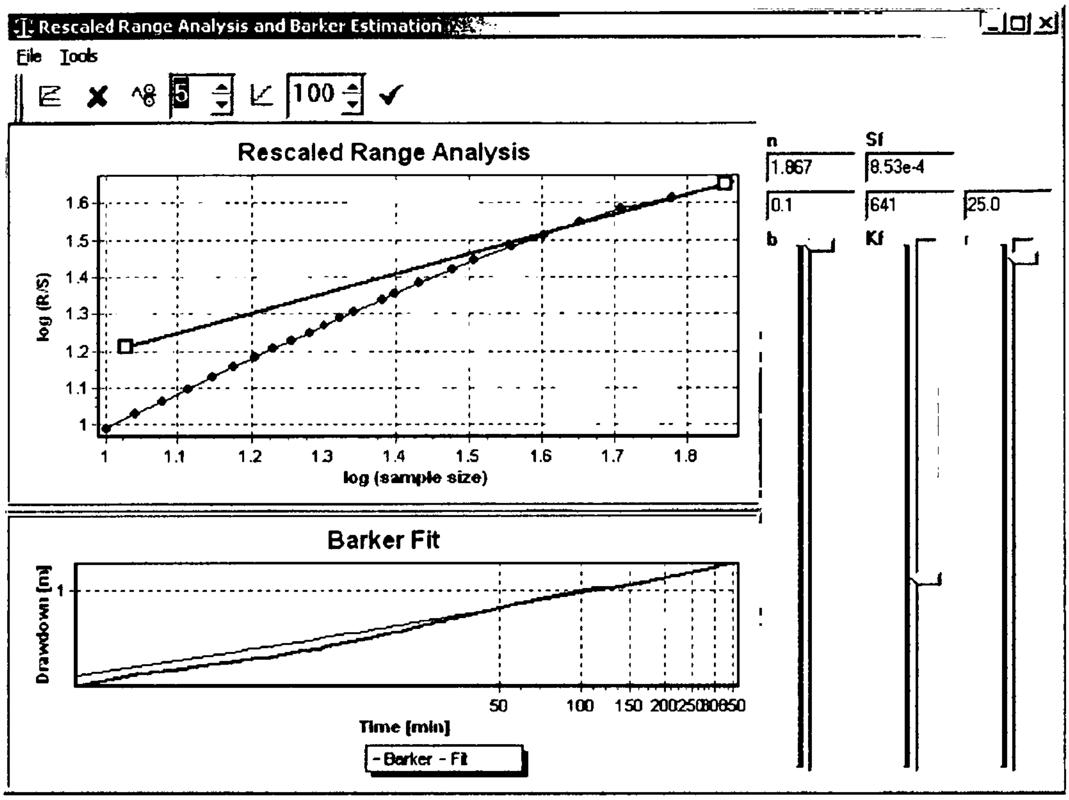


Figure 4-7(b). Pumping test analysis screen for the comprehensive assessment

The results of the assessment for various pumping rates over a period of 1 and 2 years respectively are shown in Figure 4-8.

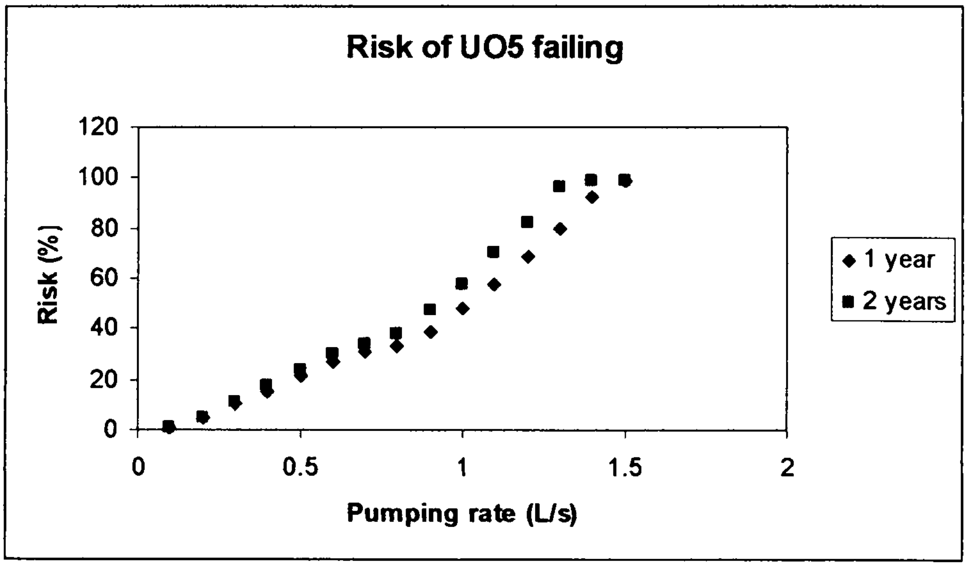


Figure 4-8. Risk of borehole UO5 failing (comprehensive assessment)

Figure 4-9 shows the results of the rapid, intermediate and comprehensive assessment after 2 years. The rapid assessment does not take into account all the boundaries and uses elementary methods to calculate values, therefore the risks are lower than those of the intermediate assessment. The intermediate assessment basically uses the transmissivity of the matrix to calculate the risks, and its risks are therefore higher than the comprehensive assessment which takes the fracture into account.

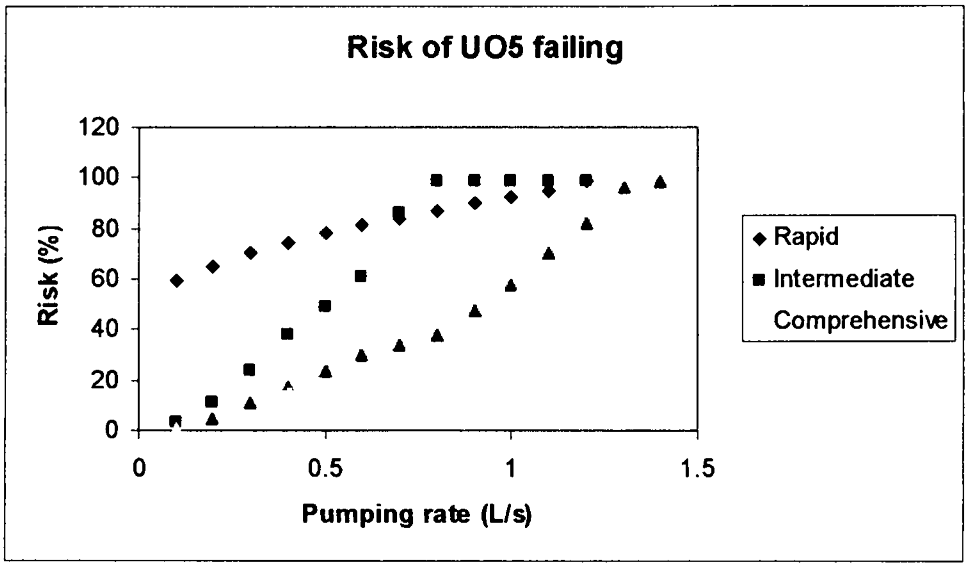


Figure 4-9. Comparison of risks after pumping for 2 years for the rapid, intermediate and comprehensive assessments.

NOTE:

- The Earth model has not been used in this assessment, although it is also a curve fitting method. The format for the required data file is documented in Appendix A, Section A8.
- The radius of influence of the borehole under investigation can be viewed after the risk has been calculated, the user just has to select "geographic data".

Chapter 5

Groundwater Contamination Risk Assessment

5.1 GENERAL

Contamination releases to groundwater can occur by design, by accident, or by neglect. Most groundwater contamination incidents involve substances released at or slightly below the surface of the earth. The protection of groundwater quality is complex and, as groundwater is affected by virtually every activity of society, it is difficult to develop and implement effective methodologies to determine groundwater contamination risks. In addition, many potential hazardous contaminants are colourless, odourless and tasteless and therefore difficult to detect by passive means (Barcelona *et al.*, 1988). In spite of all these problems, a comprehensive, integrated approach to groundwater protection is essential if groundwater quality standards for the highest beneficial use are to be met and maintained (Lynch *et al.*, 1994).

Not all land-use activities pose the same contamination threat to groundwater resources and different parts of the environment have varying capacities for dealing with contamination. Consequently, it is necessary to review the risk of groundwater contamination in two separate but interrelated ways, namely considering the characteristics of the contaminant and considering the vulnerability of the aquifer to contamination. The characteristics of the contaminant include the source of the contaminant, its loading as well as information about the contaminant itself. Aquifer vulnerability, on the other hand, represents the intrinsic characteristics that determine the sensitivity of an aquifer to the adverse effects resulting from the imposed contaminant (Lynch *et al.*, 1994). The groundwater contamination risk assessment therefore consists of a vulnerability assessment and a contaminant assessment.

5.1.1 Aquifer Vulnerability

An approach similar to that of DRASTIC (Rosen, 1994) was followed to determine the vulnerability of an aquifer. The parameters needed for describing vulnerability are:

- Depth to groundwater: this gives an indication of the distance and time required for the contaminant to move through the unsaturated zone to the aquifer.
- Recharge: the primary source of groundwater is precipitation which aids the movement of a contaminant to the aquifer.
- Aquifer media: the consolidated or unconsolidated rock matrices that serve as water-bearing units. In this approach, the fractures that occur in the rock matrix will also be taken into account.
- Soil media: this consists of the upper portion of the vadose zone (Aller *et al.*, 1987). The soil media can affect the rate at which contaminants migrate to groundwater.
- Topography: will give an indication on whether a contaminant will run off or remain on the surface long enough to infiltrate into the groundwater.
- Impact of the vadose zone: this is defined as that portion of the geological profile beneath the earth's surface and above the first principal water-bearing aquifer (Lynch *et al.*, 1994). The vadose zone can retard the progress of the contaminant.

5.1.2 Contaminant Assessment

The following information regarding the contaminant and the effects thereof are taken into account in the contamination assessment:

- Contaminant: according to the National Water Act (Act No 36, 1998), pollution is defined as the direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it –
  - *(a) less fit for any beneficial purpose for which it may reasonably be expected to be used; or*
  - *(b) harmful or potentially harmful –*
    1. *to the welfare, health or safety of human beings;*
    2. *to any aquatic or non-aquatic organisms;*
    3. *to the resource quality; or*

4. *to property.*

As the National Water Act (Act No 36, 1998) emphasises the importance of basic human needs and aquatic ecosystems, the drinking water guidelines (DWAF, 2001) and aquatic ecosystem guidelines (South African Water Quality Guidelines, 1996) will be used as a basis to determine the potential impacts of a certain contaminant.

- Duration of contamination: if the contamination results from a single (once-off) spill, the impact will probably be smaller than that resulting from continuous contamination.
- Contaminant properties: these include aspects such as:-
  - Matrix diffusion: the process of solute diffusion from fractures with high solute concentrations to the rock matrix, which has a lower solute concentration.
  - Dispersion: a measure of the spreading of a flowing substance due to the nature of the rock matrix with its interconnected channels distributed randomly in all directions.

Figure 5-1 summarises the steps in the groundwater contamination risk assessment.

5.2 DATA REQUIREMENTS

According to the definition of a rapid assessment, low levels of confidence are attached to the results and no intensive field investigations are necessary. Therefore the data requirements are limited and the assessment will rely heavily on data from the datasheets stored in the database of the decision tool. These datasheets are documented in Appendix B. At least one field investigation is attached to the intermediate assessment. For high confidence results, a comprehensive assessment has to be completed, for which good quality data, based on intensive field investigations, is necessary. Table 5.1 contains the data required for a contamination risk assessment.

Groundwater contamination risk assessment

Problem formulation

Hazard identification establishes whether exposure to a contaminant can cause groundwater contamination. Once a hazard has been identified, the remainder of the process encompasses the description of the properties of the hazardous agent and the vulnerability of the aquifer.

Questions to be asked: What is the problem? Why is it a problem?

Analysis

Aquifer Vulnerability
Establishes the tendency or likelihood for contaminants to reach a specified position in the groundwater system after introduction at some location above or in the aquifer.

Contaminant Assessment
Establishes the frequency, duration and potential impacts (on human health and aquatic ecosystems) of contamination, taking into account the properties of the contaminant.

Risk characterisation

Provides an indication of the incidence of possible contamination taking into account properties of both the aquifer and the contaminant. Risk characterisation should include information that is useful to both stakeholders and risk managers.

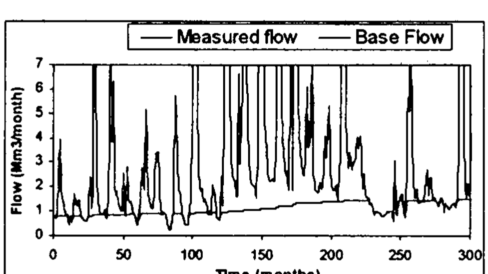


Figure 5-1. Summary of methodology for contamination risk assessment

Table 5.1: Data required for contamination risk assessment and potential data sources

Data required	Potential data sources		
	Rapid	Intermediate	Comprehensive
Vulnerability Assessment			
• Depth to groundwater	User	User	User
• Recharge	Map[1]/User	Map[1] OR	
o Rainfall	-	User	User
o Chloride in rainfall	-	Laboratory analyses	Laboratory analyses
o Chloride in groundwater	-	Laboratory analyses	Laboratory analyses
o Water levels in boreholes	-	-	OR Field data
• Aquifer media	Geological map/User	Borehole logs/augering	Borehole logs
• Soil media	Soil map[2]/User	Soil map[2]/Laboratory analyses	Laboratory analyses
• Topography	Topographical map/User	Topographical map/Field data	Field data
• Vadose zone information	DT database[3]	DT database[3]/Field data	Field data
Contaminant Assessment			
• Contaminant	User	User	User
• Position of source	-	User	User
• Concentration at source	-	Laboratory analyses	Laboratory analyses
• Contaminant injection rate	-		User
• Drinking water guidelines	DT database[4]	DT database[4]	DT database[4]
• Aquatic ecosystem guidelines	-	DT database[4]	DT database[4]
• Position of boreholes	-	User	User
• Abstraction rates	-	User	User
• Diffusion/matrix diffusion values	DT database[5]	DT database[5]/experiments	Experiments
• Dispersivity values			Calibration of equations
o Migration distance	DT database[6]/User	DT database[6]/User	
• Groundwater gradient	-	User	User
• Hydraulic conductivity	-	DT database[8]/user	User to determine from pumping tests
• Thickness of aquifer	-	-	User
• Area over which contamination is taking place	-	-	User
• Porosity	-	DT database[9]/user	User from tracer test or laboratory experiments
• Duration of contamination	User to choose from DT database[7]	User	User

-Data not needed for assessment. [1]Map included in DT (see Appendix A, Section A1).
[2]Map included in DT (see Appendix B, Section B1). [3]See Table 5.3.
[4]See Appendix B, Section B2. [5]See Appendix B, Section B3.
[6]See Appendix B, Section B4. [7]See Table 5.3.
[8]See Appendix B, Section B7. [9]See Appendix B, Section B8.

5.3 ASSUMPTIONS AND LIMITATIONS

Rapid Assessment

For the rapid assessment, no chemical analyses are needed and the concentrations of the contaminants are therefore not included in the assessment. If there are also no field observations for the data discussed in Table 5.1, then values from maps or the literature recorded in the DT database can be used. However, such an assessment cannot be used to make accurate conclusions concerning the contamination risk.

Only drinking water guidelines are used in this assessment.

Intermediate Assessment

This is a medium confidence assessment based on limited field data. In general, no time series data will be available. When calculating the concentration of contamination at any point in the aquifer, only advective-dispersive processes are taken into account.

The aquatic ecology and drinking water guidelines are considered in the intermediate assessment.

Comprehensive Assessment

A comprehensive assessment is a quantitative assessment and high confidence is attached to the results. Intensive field investigations are therefore necessary. Even with all the field data, it is impossible to record and include all heterogeneities present in the aquifer.

Laboratory experiments and tracer tests must be conducted to determine accurate contaminant parameters such as matrix diffusion and porosity. Tracer tests can also be used to determine the influence of fractures in the movement of contamination. Two types of tracer tests are discussed in Chapter 2. The analyses of these are not included in the DT tool, however the Institute for Groundwater Studies is developing software to analyse these tests, and this will shortly be available.

The aquatic ecology and drinking water guidelines are taken into account in the comprehensive assessment.

The equations that are used to calculate contaminant concentrations assume that there is a uniform flow rate through the aquifer.

General – applicable to all assessments

Due to the shortage of information concerning membership functions, the functions will be presumed to be cosine or specific values will be assigned to specific conditions. The methodology only takes into account chemical contamination, specifically matrix diffusion and dispersion. All other chemical processes/reactions are ignored.

If there are no impacts on the ecology or human health, the risk of contamination is assumed to be zero.

5.4 METHODOLOGY

The methodology is the same as discussed in Section 3.2. Therefore it is once again necessary to set up decision rules and membership functions, which are the same for all tiers of the assessment. However the quality of data and calculation of concentrations vary for the three different assessments. The recharge and concentrations calculations needed for the assessments are discussed in Table 5.2.

The vulnerability and contaminant assessment membership functions/values are listed in Tables 5.3 and 5.4 respectively. Where possible the DRASTIC ratings have been used (Lynch *et al.*, 1994), but where necessary experts (B Usher and G van Tonder from the Institute for Groundwater Studies, University of the Free State) in groundwater contamination were consulted to establish the decision rules and membership functions/values.

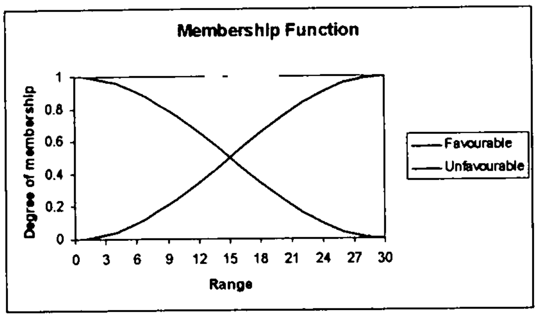
Table 5.2: Calculations needed for the contamination assessment

<table>
<tr><th rowspan="2">Data required for calculations</th><th colspan="3">Calculations</th></tr>
<tr><th>Rapid assessment</th><th>Intermediate assessment</th><th>Comprehensive assessment</th></tr>
<tr><td>Recharge: Annual rainfall for both the rapid and intermediate assessments.
Chloride values in rainfall and groundwater for the intermediate and comprehensive assessments.
Time series groundwater levels and rainfall data for the comprehensive assessment.</td><td>Recharge is calculated directly from Vegter's recharge map (Vegter, 1995).</td><td>Recharge is calculated directly from Vegter's recharge map (Vegter, 1995).
OR
Recharge is calculated using the chloride method (Appendix A, Section A4).</td><td>Recharge is calculated using the chloride method (Appendix A, Section A4).
OR
Recharge is calculated using the EARTH method (Appendix A, Section A4).</td></tr>
<tr><td>Concentration: Determines the impacts of the contaminant on humans and the ecology.
No information is needed for the rapid assessment.
For the intermediate assessment the following is needed:
• Initial concentration at the source (C_0).
• Length between borehole and source (L) or source coordinates.
• Migration distance to calculate dispersivity values (α).
• Duration of contamination (t).
• Groundwater gradient (dh/dl), effective porosity (n_e) and hydraulic conductivity (K) to determine velocity (v).
• Dispersivity (α) and velocity (v) to determine the dispersion coefficient (D).
For the comprehensive assessment the following is needed:
• Initial concentration at the source.
• Positions of source and boreholes.
• Duration of and injection rate of contaminant.
• Area of source and thickness of aquifer.
• Groundwater gradient, effective porosity and hydraulic conductivity to determine velocity.
• Dispersion coefficients.
• Concentration at point in aquifer together with coordinates of point and time at which the concentration was measured.</td><td>-</td><td>The equation used to calculate concentrations is in the following format (Fetter, 1999):
$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - vt}{2\sqrt{Dt}}\right)\right]$$
where $D = \alpha v$ and
$$v = \frac{K}{n_e}\frac{dh}{dl}.$$</td><td>Two calculations will be used for the following contamination sources:
• Continuous injection
• Slug (once-off) injection
For information concerning the equations used in this section refer to Appendix B (Section B5). It is important to note that dispersion coefficients must be determined by means of the equations in Appendix B (Section B5).</td></tr>
</table>

Table 5.3: Membership functions/values for decision rules for vulnerability assessment

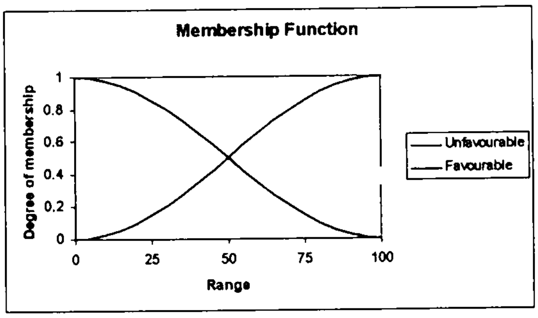
Vulnerability membership functions/values

Depth to groundwater[1] (m)



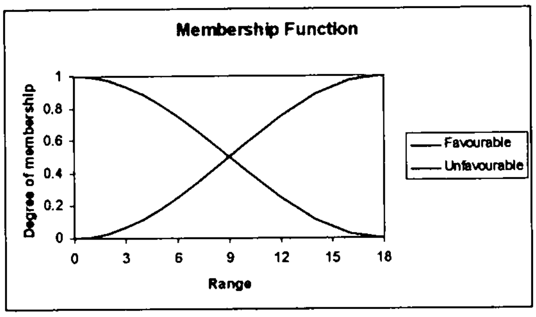
Unfavourable limit	Favourable limit
0	30

Recharge[1] (mm/year)



Unfavourable limit	Favourable limit
100	0

Topography[1] (%)



Unfavourable limit	Favourable limit
0	18

Soil media[1]

Type[2]	Membership
SaCl, SaCl-Cl	0.6
SaClLm-Cl, SaClLm-SaCl	0.6
SaClLm, SaLm-SaCl	0.5
SaLm-SaClLm	0.5
SaLm	0.4
Sa-LmSa, SaLmSa etc	0.35
Sa-SaLm, LmSa-SaLm, LmSa	0.3
Sa	0.0

Aquifer Media[1]

Type	Membership
Dolomite (massive)	1.0
Intergranular	0.2
Fractured	0.4
Fractured and weathered	0.7
Dolomite (karstic)	0.0

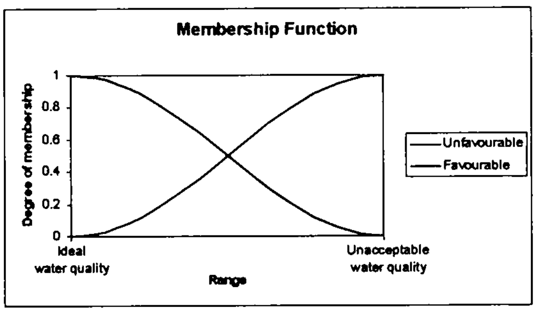
Impact of the vadose zone[1]

Type	Membership
Beach sands and Kalahari	0.0
Dolomite	0.1
Table Mountain, Witteberg, Granite, Natal, Witwatersrand, Rooiberg, Greenstone, Dominion, Jozini	0.4
Karoo (southern)	0.5
Ventersdorp, Pretoria, Griqualand West, Malmesbury, Van Rhynsdorp, Uitenhage, Bokkeveld, Basalt, Waterberg, Soutpansberg, Karoo (northern), Bushveld, Olifantshoek	0.6
Gneiss, Namaqua metamorphic rocks	0.7

[1]Taken from Lynch *et al.* (1994). [2]Sa = sand, Lm = loam, Cl = clay.

The decision rules, taking into account the above parameters for the vulnerability assessment, are documented in Appendix E (Section E2). The aquifer vulnerability risk is then calculated using Equation 3.1.

Table 5.4: Membership functions/values for decision rules for contaminant assessment

<table>
<tr><th colspan="2">Contaminant assessment membership functions/values</th></tr>
<tr><th>Contaminant[1]</th><th>Contamination duration</th></tr>
<tr><td>


Unfavourable limit — Unacceptable water
Favourable limit — Ideal water quality
</td><td>
Type — Membership
Contamination may be seconds, minutes or hours — 0.9
Contamination occurs at intermittent periods < 2 years — 0.6
Contamination > 90 days and < 2 years — 0.6
Contamination occurs at intermittent periods >2 years — 0.3
Continuous contamination > 2 years — 0.0
</td></tr>
<tr><th colspan="2">Contaminant properties</th></tr>
<tr><th>Range[2]</th><th>Membership value</th></tr>
<tr><td>Very high</td><td>0.2</td></tr>
<tr><td>High</td><td>0.4</td></tr>
<tr><td>Medium</td><td>0.6</td></tr>
<tr><td>Low</td><td>0.8</td></tr>
<tr><td>Very low</td><td>1.0</td></tr>
</table>

[1]Taken from Quality of Domestic Water Supplies (2001). Appendix B (Section B2) contains more information. For the rapid assessment, concentrations are not needed therefore the contaminants are classified according to death (0.0), effects common (0.25), long-term effects (0.4) and few effects (0.8).
[2]For the calculation of the ranges refer to Appendix B (Section B6).

The risk of contamination based on the contaminant characteristics is calculated using Equation 3.1. The decision rules on which the calculations are based are listed in Appendix E (Section E2).

The overall groundwater contamination risk assessment can then be calculated by means of the following condition:

$$\text{Risk}_{\text{contamination}} = \max(\text{Risk}_{\text{vulnerability}}, \text{Risk}_{\text{contaminant}})$$

5.5 EXAMPLE

The Campus Test Site is once again taken as an example for the contamination assessment. A vulnerability assessment will be conducted to determine the risk of contamination based on the aquifer properties. All three tiers of the assessment are similar except for the method by which the recharge is calculated and the quality of data required. As the recharge calculations were discussed in the sustainable assessment, only the rapid vulnerability risk assessment will be demonstrated here.

The input for the vulnerability risk is summarised in Table 5.5.

Table 5.5: Input data for rapid vulnerability risk assessment

Input	Value
Recharge (mm/year)	Select from map
Soil media	Select from map
Aquifer media	Fractured
Vadose zone	Karoo (southern)
Groundwater depth (mbgl)	10
Topography (% slope)	0.3

The results of the risk assessment are shown in Figure 5-2.

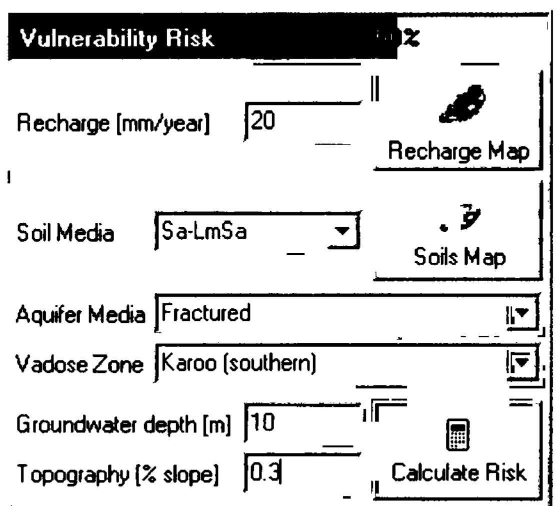


Figure 5-2. Results of rapid vulnerability assessment

It is important to note that this risk in the rapid assessment might differ slightly from that in the intermediate and comprehensive assessments as the quality of data required for the latter two assessments is better than that required for the rapid assessment.

There is a difference between the rapid assessment, and the intermediate and comprehensive contaminant assessments. Therefore, an example of both the rapid and intermediate assessments will be discussed.

For the rapid contaminant assessment, the example of a spill of tricholoroethane will be considered. Trichloroethane, also known as methyl chloroform, does not occur naturally in the environment. It is found in many common products such as glue, paint, industrial degreasers and aerosol sprays. The maximum drinking water guideline is 0.2 mg/L.

The data needed for the rapid assessment are listed in Table 5.6.

Table 5.6: Input data for rapid contaminant risk assessment

Input	Value
Duration of contamination	Polluting > 90 days and < 2 years
Contaminant	tricholoroethane
Matrix diffusion value[1] (m^2/s)	1.01×10^{-9}
Dispersivity[2] (m)	50

[1]This value is assumed and has not been calculated. A value can also be chosen from the DT database. [2] Migration distance can also be given and then DT will calculate dispersivity.

The results of the rapid risk assessment are shown in Figure 5-3.

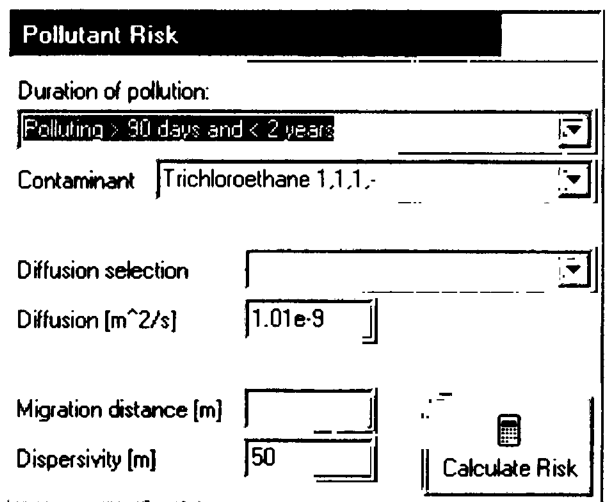


Figure 5-3. Results of rapid contaminant assessment

The total rapid contamination risk is calculated as:

$$Risk_{contamination} = \max(Risk_{vulnerability}, Risk_{contaminant}) = 67\%$$

As the Campus Test Site has a fracture at 21 m, two scenarios will be completed for the intermediate contaminant assessment, the first being the movement of the contaminant through the fracture, and the second the movement of the contaminant through the sandstone matrix. The risk of borehole UO5 being contaminated is calculated assuming borehole UO5 is not being pumped. In addition, there are no aquatic ecosystems in the vicinity, so the risk will be calculated based on drinking water guidelines. For the intermediate contaminant risk assessment, the data documented in Table 5.7 was used. A concentration of 10 mg/L was assigned at the source.

Table 5.7: Input data for the intermediate contaminant risk assessment

Input	Fracture	Matrix
Position of source	X = -78393.61 Y = -21571.02	X = -78393.61 Y = -21571.02
Position of borehole UO5	X = -78893.61 Y = -21071.02	X = -78893.61 Y = -21071.02
Contaminant	tricholoroethane	tricholoroethane
Concentration at source (mg/L)	10	10
Matrix diffusion value[1] (m^2/s)	1.01×10^{-9}	1.01×10^{-9}
Porosity (%)	49	6
Hydraulic conductivity (m/d)	200	2
Groundwater gradient	0.003	0.003
Duration of contamination	Polluting > 90 days and < 2 years	Polluting > 90 days and < 2 years

[1]This value is assumed and has not been calculated. A value can also be chosen from the DT database.

The results of the assessment are listed in Table 5.8. It is clear that the contaminant moves faster along the fracture zone. The DT holds the risk at 12% due to the contamination duration being continuous and the contaminant properties not being favourable. Once the contaminant reaches borehole UO5 the risk start increasing. An example of the intermediate assessment screen is shown in Figure 5-4.

Table 5.8: Results of intermediate contaminant assessment

Time (years)	Risk (%)	
	Fracture	Matrix
0.25	12	12
0.5	23	12
0.625	69	12
0.75	99	12
6	99	21
7	99	50
8	99	98
8.5	99	99

The "plus" sign buttons in Figure 5-4 are used to add contaminants for the assessment. If more than one contaminant is selected, the DT will calculate the risk for each one. The final risk will then be the maximum of the individual risks calculated. The input screen for the geographical data is similar to that used in the sustainable risk assessment except that the source is depicted in a red square.

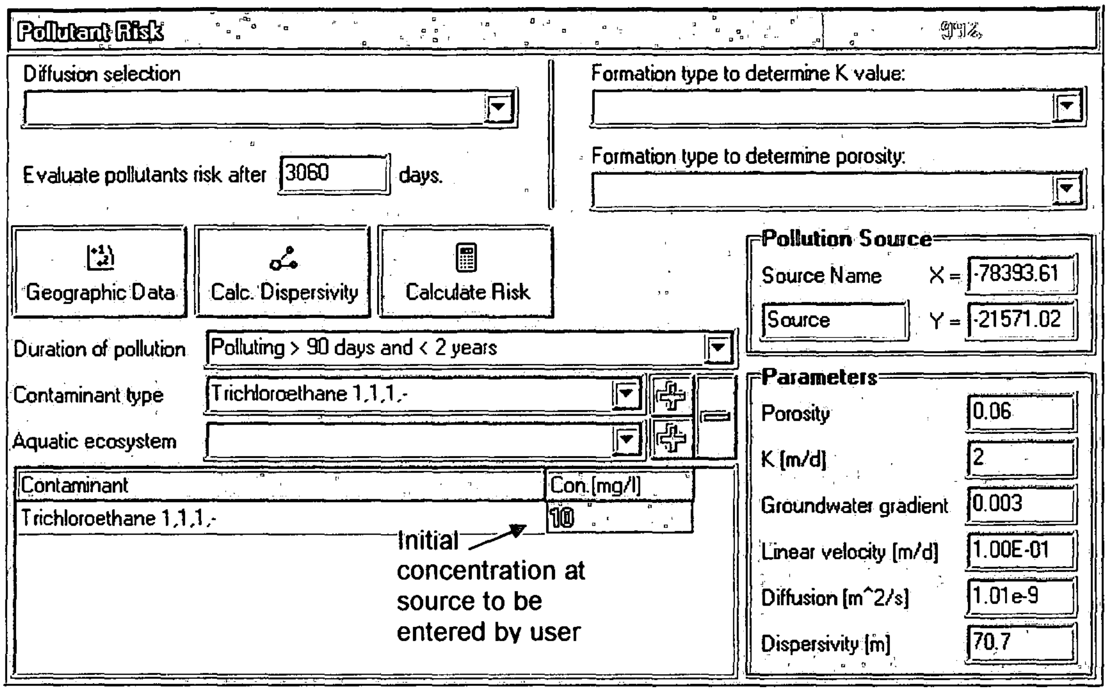


Figure 5-4. Input screen for the intermediate contaminant risk assessment

The comprehensive contaminant assessment is almost identical to the intermediate assessment except, that the user can select either a slug source or a continuous source. It is important to note that with the slug source the contamination moves through the aquifer as a pulse and once the maximum concentration has passed a point in the aquifer, the risk will start decreasing at that point. The dispersivity is calculated by means of a mass transport equation documented in Appendix B, Section B5.

5.6 MINES

5.6.1 Background

There are basically two types of mines found in South Africa, namely open cast mines and underground mines. Underground mining can be assessed with the DT, but open cast mines can decant. The water quality of the decanting mines can have a major impact on human health and the environment. This poor quality water usually flows down gradient toward surface water bodies. The sulphate values in decanting water are usually high and can cause dehydration and diarrhoea in humans. Neither South Africa nor the United States Environmental Protection Agency has aquatic ecosystem guidelines for sulphates.

5.6.2 Methdology

Open cast mines, the majority of which are coal mines in South Africa, fill up with water and decant after closure. In the South African coal mines this normally occurs within 10 years of closure. At the more isolated collieries, rebound of groundwater can take up to 50 years (Grobbelaar, 2000).

As the quality of decanting groundwater is important, it will be discussed in this section and included in the decision tool. No fuzzy logic calculations are required as the decant rate is a relatively easy to calculate. The drinking water guidelines specified for sulphates will be used to determine the risks associated with the quality of decanting water.

The data requirements for determining the amount of water that will decant and the quality thereof are listed in Table 5.9.

The amount of water that will decant is calculated with the following Equation (Van Tonder, 2001(a)):

$$\text{Decant rate} = (\text{R} \times \text{area of mine}) + \text{I} - \text{O}$$

where

R = Effective recharge

I = Inflow of groundwater into the mine

O = Outflow of groundwater out of the mine

The time taken for decanting to start once mining operations have ceased can be calculated as:

$$\text{Time} = \frac{\text{volume of open cast mine} \times \text{storavity of spoils}}{\text{I} + \text{R}}$$

The concentration of sulphate present in groundwater decanting can then be determined as:

$$\text{Concentration} = \frac{\text{SO}_4\ \text{generation} \times \text{area of mine}}{\text{decant rate}}$$

The amount of mixing in a river can be determined as:

$$\text{Mixing} = \frac{\text{Load of sulphate at river}}{\text{Low flow in river}}$$

where the load of sulphate at the river is calculated as:

$$\text{Load of sulphate at river} = \text{Concentration} \times \text{decant rate}$$

Table 5.9: Data required for determining decanting and possible data sources

Data required	Rapid assessment	Intermediate assessment	Comprehensive assessment
Storativity of spoils	Assumed to be 25%	Assumed to be 25%	User
• Recharge o Rainfall o Chloride in rainfall o Chloride in gw o Water levels in boreholes	Map[1]/User - - - -	Map[1] OR User Laboratory analyses Laboratory analyses -	 User Laboratory analyses Laboratory analyses OR Field data
Area of mine Depth of mine	User User	User User	User User
Flow into and out of the mine • Groundwater gradient • Hydraulic conductivity • Aquifer thickness • Transmissivity - Pumping test data - Slug test data • Length of mine circumference where groundwater is flowing into the mine • Length of mine circumference where groundwater is flowing out of the mine	 User User/DT database[2] User - - - User User	 User - - User to be determined using Logan's method OR User User User	 User to be determined from Bayesian interpolation[3] - - User to be determined using Cooper-Jacob method - User User
Amount of sulphate generated	Assume to be 7 kg/d/ha (Hodgson, 2001)	Assume to be 7 kg/d/ha (Hodgson, 2001)	Field data
Low flow • Quaternary catchment • Low flow	 User	 User	 User OR User

[1]Refer to Appendix A, Section A1.
[2]See Appendix B, Section B7.
[3]Can be determined using software package Tripol, developed at the Institute for Groundwater Studies. This software can be accessed via the DT.

The risks can then be determined based on drinking water standards. These are determined by means of a cosine function (see Figure 5-5).

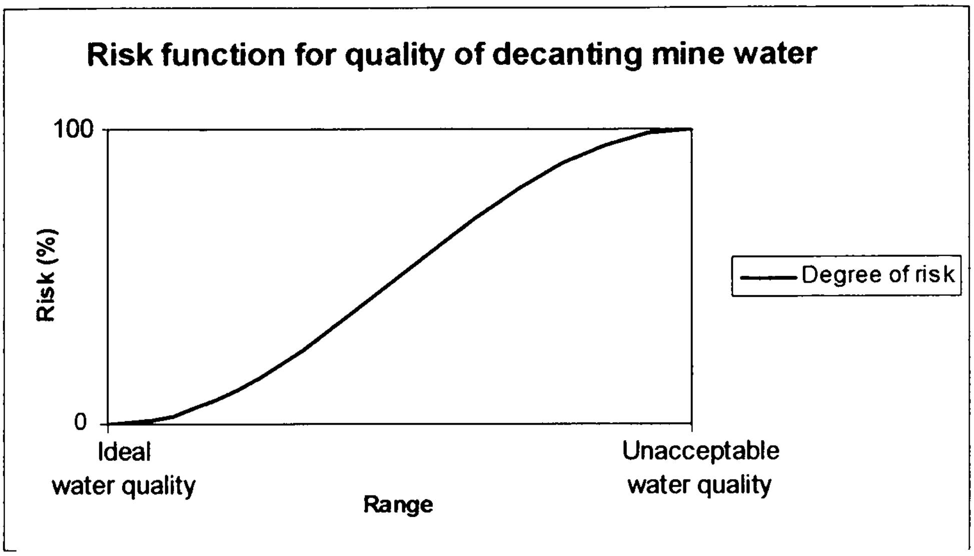


Figure 5-5. Risk function for sulphate load in decanting mine water

5.6.3 Example

The three tiers of assessment are similar and therefore a hypothetical open cast mine with the parameters listed in Table 5.10 will be used for the rapid assessment to calculate the risk of contamination in the river as a result of decanting. The input screen and results of the risk assessment are shown in Figure 5-6.

Table 5.10: Data needed for the open cast mine contamination risk assessment

Input	Value
Length of outflow (m)	500
Length of inflow (m)	500
Depth of mine (m)	25
Area of mine (ha)	25
Groundwater gradient	0.02
Transmissivity (m^2/d)	13
Quaternary catchment	B41B
Recharge determined from Vegter's map (mm/year)	32

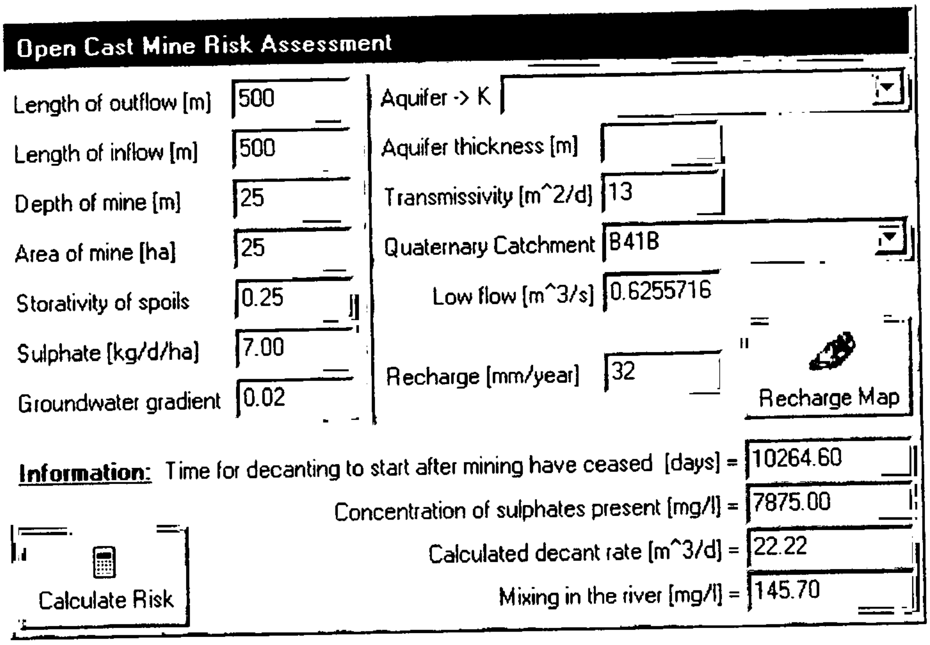


Figure 5-6. Open cast mine risk assessment

Chapter 6

Health Risk Assessment

6.1 INTRODUCTION

A health risk assessment is the process or method of determining if an activity (man-made or natural) will negatively impact human health. As such a health risk assessment is a decision making tool. It provides the analytical support for decisions that protect public health (Schwab and Genthe, 1998).

The scope and nature of a health risk assessment varies – from broadly based scientific conclusions about arsenic affecting the whole nation to site-specific findings concerning the same chemical in the local water supply.

Lung disease, cancers and chronic poisoning are some of the hazards associated with chemicals and dusts in projects ranging from the application of agricultural chemicals to quarrying and mining. Exposure may occur at both places of occupation and residence through unregulated emissions to various media (in this case groundwater), or through the inappropriate use of machinery, for example leaking engines. In some instances, projects with obvious health benefits may also have unintentional health impacts. Water supply projects, for example, will often reduce the occurrence of diseases such as diarrhea and cholera, but if incorrectly sited and managed, may induce other diseases. For example when a wellfield is located close to fertilized crops, the nitrate in the groundwater can cause methyglobinemia, a type of anaemia, which can be fatal for infants.

A groundwater health risk assessment can be defined as a qualitative or quantitative process to characterise the probability of adverse health effects associated with measured or predicted levels of hazardous agents in groundwater. Once a contaminant is released into the groundwater, its resultant concentrations found in the human body is dependent upon the physical and chemical properties of both the contaminant and the groundwater. In addition the concentrations found in a human are subject to the person's exposure to groundwater. Exposure is defined by the frequency, magnitude and duration of contact with the contaminant. Frequency refers to whether a person is exposed daily or just occasionally. The magnitude refers to the amount of exposure; occupational exposure will be greater than community exposure. The duration refers to whether any single exposure episode may last for minutes, hours, days or years. Once the contaminant is inside the body it may be further transformed via metabolism or detoxification. The ability to transform chemicals varies. Children, the elderly and those with chronic conditions, for instance, react differently to the same dose than the average, healthy middle-aged adult (Schwab and Genthe, 1998). The impact of contaminants for the various scenarios are characterised in a health risk assessment.

A health risk assessment consists of problem formulation (hazard identification), analysis and risk charaterisation. Figure 6-1 is a summary of these.

6.2 DATA REQUIREMENTS

Unlike groundwater risk assessments, there is a large difference in the methods used to calculate the three tiers of health risks. However, they will all use fuzzy logic rules to some degree.

According to the definition of a rapid assessment, low levels of confidence are attached to the results and no intensive field investigations are necessary. Therefore the data requirements are limited and the assessment will rely heavily on data stored in the DT database. One of the main differences between the rapid and intermediate assessment is the quality of data required for the assessments. Table 6.1 is a summary of the data required for the assessments.

Groundwater health risk assessment

Problem formulation

Hazard identification establishes whether exposure to a chemical, radioactive or microbiological agent can cause harm. This step determines whether the risk assessment should be continued or abandoned. Once a health hazard has been identified, the remainder of the process encompasses the description of the properties of the hazardous agent, and the identification of its health effects.

Questions to be asked: What is the problem? Why is it a problem? How was the problem first recognised? What are the effects on human health? How urgent is the need for action?

Analysis

Exposure Assessment

Establishes the intensity, frequency and duration of human contact with a contaminant. To determine exposure, it is necessary to combine an estimation of environmental concentrations of the hazards with demographic or behavioral descriptions of the exposed population.

Dose-response Assessment

Characterises the relationship between the dose of a hazardous agent (ie the amount of pollutant taken into the body through breathing, ingestion and skin contact) and incidence of an adverse effect in the exposed population.

Risk characterisation

Provides an indication of the incidence of the health effect under the conditions of exposure described in the exposure assessment and identified dose-response relationship. Risk characterisation should include information that is useful to both stakeholders and risk managers. *Questions to be asked:* What is the nature and likelihood of the health risk? Which individuals or groups are at risk? How severe are the anticipated adverse effects? What scientific evidence supports the conclusions about the risk? How strong is the evidence?

Figure 6-1. Methodology for a groundwater health risk assessment

Table 6.1: Data required health risk assessments and potential data sources

Data Required	Potential data sources		
	Rapid	**Intermediate**	**Comprehensive**
Chemical	User to choose from list in DT[1]	User to choose from list in DT[2 and 3]	User to choose from list in DT[2 and 3]
• Concentration	-	Laboratory analyses	Laboratory analyses
∘ Cancer potency factor	-	DT database[2]	DT database[2]
• Reference dose	-	DT database[3]	DT database[3]
Microbiological agent	User to choose from list in DT[4]	User to choose from list in DT database[5]	User to choose from list in DT database[5]
• Number of organisms	-	Laboratory analyses	Laboratory analyses
• α and β or r	-	DT database[5]	DT database[5]
Radioactive element	User to choose from list in DT	User to choose from list in DT database[6]	User to choose from list in DT database[6]
• Concentration	-	Laboratory analyses	Laboratory analyses
• Risk coefficient	-	DT database[6]	DT database[6]
Exposure duration	User to choose from values in DT[7]	User	User
Population subgroup	User to choose from values in DT[7]	-	-
Population size	User to choose from values in DT[7]	User to obtain from local authorities	Field survey
Average intake rate	-	Average values documented in DT database[8]	Field data
Body weight	-	Average values documented in DT database[8]	Field data
Life time age of person	-	Average values documented in DT database[8]	Field data

[1]Refer to Appendix C, Section C1 and Appendix B, Section B2.
[2]Refer to Appendix C, Section C2.
[3]Refer to Appendix C, Section C3.
[4]Refer to Appendix C, Section C4.
[5]Refer to Appendix C, Section C5.
[6]Refer to Appendix C, Section C6.
[7]Refer to Table 6.2.
[8]Refer to Appendix C, Section C7.

6.3 ASSUMPTIONS AND LIMITATIONS

The assumptions and limitations for the various assessments differ and will therefore be discussed separately.

Rapid Assessment

- As this is a rapid assessment, no analyses are needed, therefore the concentrations (or dose) of the chemicals, radioactive and microbial agents are not included in the assessment.

- In addition exact exposure durations are not included in the calculations.
- The exposure pathway (oral, dermal and inhalation) is not taken into account.

Intermediate Assessment

- It is assumed that an adult weighs 70 kg,
- It is assumed that a child weighs 10 kg,
- It is assumed that a person drinks 2 liters of water a day,
- It is assumed that a person inhales 20 m^3 of air a day,
- It is assumed that the average lifetime of human is 70 years.

General – applicable to all assessments

- Only direct exposure (oral, dermal or inhalation) to groundwater are considered. Indirect pathways are not taken into account, for example eating foods irrigated with contaminated groundwater.
- Due to the shortage of information concerning membership functions, the functions will either be cosine or specific values will be assigned to specific conditions.
- If the pollutant is not carcinogenic, radiogenic, toxic or causes infection then health risks are considered to be zero.
- If the exposure to a pollutant is zero, then the health risks are considered to be zero.
- Only the carcinogenic effects of radioactive elements are considered.
- The radiogenic risk coefficients used in the intermediate and comprehensive assessments do not include the contribution of daughter products.

6.4 METHODOLOGY

6.4.1 General

Experts in the field highlight the following components as important when performing a health risk assessment:

- Toxicity of the contaminant: When exposed to toxic chemicals there are numerous health effects that vary from mild headaches to death, all of which need to be taken into account in a risk assessment.

- Carcinogeneity of a contaminant: Cancers traced to direct, involuntary exposure to environmental pollution are estimated to constitute about 2% of all cancer risks (Doll and Peto, 1981). However exposure to certain chemicals can cause some form of cancer and therefore the carcinogeneity of a chemical needs to be taken into account when conducting a health risk assessment.
- Possibility of infection: Allows the user to obtain an idea of the risks involved in human exposure to a variety of bacteria, viruses and protozoa. The risk of infection is 10 to 1000 times less for the bacteria than the viruses and protozoa at similar levels of exposure.
- Radiation exposure can result in delayed effects such as cancer. Some of the cancers associated with radiation are: leukemia, esophagus, stomach, colon, liver, lung, breast, ovary, urinary tract and multiple myeloma.
- Exposure to a contaminant: This establishes whether exposure to a chemical or microbiological agent can cause harm. To determine exposure, it is necessary to combine an estimation of environmental concentrations of the hazards with demographic or behavioral descriptions of the exposed population.
- Population exposed to a contaminant: The population is composed of groups who differ in their vulnerability to health hazards. For example babies are more susceptible to infection because of their lack of immunity.
- Size of exposed population: The seriousness of health risks does not only depend on the hazardous agents but also on the size of the population affected. In general the bigger the population, the more cost and effort needed to treat the resulting health impacts.

The fuzzy logic methodology will once again be used in the risk assessments, however the decision rules and membership functions will differ for the rapid assessment. Therefore this assessment will be discussed separately.

The decision rules and membership functions were determined with the assistance of one of the expert health risk assessors, Bettina Genthe from the CSIR.

6.4.2 Rapid groundwater health risk assessment

The methodology is the same as discussed in Section 3.2. Therefore it is once again necessary to set up decision rules and membership functions. The membership functions are listed in Table 6.2, and the decision rules are documented in Appendix E, Section E3.

Table 6.2: Membership functions/values for the rapid health risk assessment

Rapid Health Risk Assessment Membership Functions			
Toxic		**Infection**	
Range[1]	**Membership value**	**Range**[2]	**Membership value**
Death	0.0	Death	0.0
Effects common	0.25	Effects common	0.25
Long-term effects	0.4	Long-term effects	0.4
Few effects	0.8	Few effects	0.8
Carcinogen[3]		**Exposure duration**	
Range[4]	**Membership value**	**Exposure**	**Membership value**
A: known human carcinogen	0.0	Contamination may be seconds, minutes or hours	0.9
B1: probable human carcinogen (limited data)	0.25	Contamination occurs at intermittent periods < 2 years	0.6
B2: probable human carcinogen (inadequate data)	0.25	Contamination > 90 days and < 2 years	0.6
C: possible human carcinogen	0.5	Contamination occurs at intermittent periods > 2 year	0.3
D: Not classified as a human carcinogen	0.75	Continuous contamination > 2 years	0.0
E: Evidence that not a human carcinogen	1.0		
Population subgroups		**Size of exposed population**	
Subgroup	**Membership values**	**Number of people**	**Membership values**
Children under the age of 2 years	0.0	> 500000	0.0
Elderly over the age of 60 years	0.0	100000 – 500000	0.05
Adults with chronic conditions	0.0	10000 – 100000	0.4
Adults between 30 and 60 years	0.5	5000 – 10000	0.65
Children between 2 and 20 years	0.5	< 5000	0.9
Adults between 20 and 30 years	0.9		

[1]Taken from water quality guidelines, Appendix B (Section B2) contains more information.
[2] See Appendix C, Section C4 for more information.
[3]According to the US EPA (1994) all radioactive elements are classified as known human carcinogens (A).
[4]Taken from US EPA Classification of Carcinogens (EPA, 2000). Appendix C (Section C1) contains more information.

The rapid groundwater health risk can be determined using Equation 3.1.

6.4.3 Intermediate and comprehensive groundwater health risk assessment

The main difference between intermediate and comprehensive assessments is the quality of data. Both intermediate and comprehensive assessments involve field work and are divided into a:

- toxic assessment,
- carcinogenic assessment,
- microbiological assessment and
- radiogenic assessment.

The intermediate assessment only requires concentrations of the contaminant to be determined, while the comprehensive assessment requires information concerning the affected population and their lifestyle.

6.4.3.1 Toxic and Carcinogenic Assessment

Toxic and carcinogenic assessments take into account the routes of exposure as documented in Table 6.3.

Table 6.3: Exposure pathways considered in groundwater driven risk assessments (Maxwell *et al.*, 1998)

Routes of exposure	Groundwater exposure pathway
Ingestion	Drinking groundwater
Inhalation	Inhalation of contaminant transferred from water to vapor in air
Dermal sorption	Sorption through skin in baths and showers

Before calculating the risks associated with both these assessments, the total dose, average daily dose and lifetime average dose have to be defined. The equations used to define risks associated with human exposure to contaminated groundwater are generally based on those specified in the EPA "Risk Assessment Guidance for Superfund" (EPA, 1989).

For each pathway, the total dose that will reach a human has to be calculated. The total dose is defined as:

$$\text{Dose} = C \times IR \times ED$$

where

Dose = Total dose

C = Maximum concentration

IR = Average intake rate

ED = Exposure duration

The average daily dose is determined by dividing an estimate of the total dose accrued during the exposure duration from a pathway by an averaging time or an expected lifetime:

$$ADD = \frac{Dose}{BW \times ED}$$

where

BW = Average body weight over exposure period

Carcinogenic risk assessments are determined over a human's lifetime. Therefore the lifetime average daily dose (LADD) is calculated as:

$$LADD = \frac{\text{Total dose}}{BW \times \text{lifetime}}$$

The carcinogenic risk calculation is based on a Poisson model:

$$Risk = 1 - e^{-LADD \times CPF} \approx LADD \times CPF$$

where CPF is the cancer potency factor. The potency factor is the slope of the percentage of animals developing cancer versus the dosage level of a particular chemical. The slope of this curve is then extrapolated to the low doses expected to be encountered by humans who may be exposed to the same chemical. Because of the complex uncertainty involved with calculating the cancer potency, these values are obtained from the IRIS (EPA, 1988) database and included in the database of the DT (See Appendix C, Section C2).

The toxic risk is calculated as:

$$Risk = \frac{ADD}{RfD}$$

where

RfD = Reference dose

The reference dose is an estimate of daily exposure to the population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime. These values are documented in the IRIS database (EPA, 1988) and will be included in the DT database (See Appendix C, Section C3).

6.4.3.2 Microbiological Assessment

Microbiological contamination of water is the largest and most immediate health hazard (Genthe and Rodda, 1999). There are two models used to determine the probability or risk of infection from pathogens (Rose and Gerba, 1991):

- The single-hit exponential model

$$\text{Risk} = 1 - e^{(-rN)}$$

- The beta-distributed model

$$\text{Risk} = 1 - \left[1 + \left(\frac{N}{\beta}\right)\right]^{-\alpha}$$

where risk refers to risk or probability of infection and

N = Exposure (number of organisms).

α,β & r = Parameters characterised by dose-response curves.

In most cases the beta-distributed model is the most appropriate, however in the case of Giardia lamblia and Cryptosporidium parvum the single-hit exponential model is to be used (Rose and Gerba, 1991). Values for α,β and r are included in the database of the DT (Appendix C, Section C5).

6.4.3.3 Radiogenic assessment

The methodology followed for the radiogenic assessment is based on that documented by the US EPA (1994(a)). A radiogenic assessment is divided into two types of assessments:

- Mortality risk: the age- and gender-specific or total risk of people dying from radiation induced cancers.
- Morbidity risk: the age- and gender-specific or total incidence of radiation induced cancers.

Both risks will be calculated. However, the higher of the risks will be used in the decision rules. In most cases this will be the morbidity risk.

The risk calculations are based on a risk coefficient (r) developed by the US EPA (1994(a)). The risk coefficients represent an estimated radiogenic cancer risk, reflecting the age and gender distribution. The coefficients can be used for short-term and long-term exposures.

For a selected exposure scenario, the calculated risk involves the multiplication of the applicable risk coefficient by the dose:

$$\text{Risk} = r \times \text{Dose}$$

The above equation is correct for inhalation and ingestion. However for submersion the risk coefficient is expressed not only in terms of becquerel but also in terms of volume and time, therefore the submersion risk is calculated as:

$$\text{Risk} = r \times C \times ED$$

6.4.3.4 Intermediate and Comprehensive Health Risk Calculations

The intermediate and comprehensive assessments take into account the carcinogenic, toxic, microbial and radiogenic risks together with the size of the population. The membership functions/values are listed in Table 6.4 and the decision rules are documented in Appendix E, Section E3. The final risk is calculated using Equation 3.1.

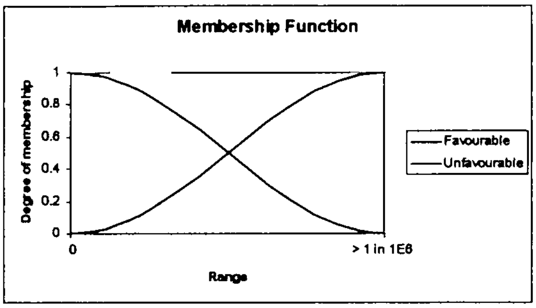
6.5 EXAMPLE

Consider a rapid assessment example of hypothetical water supply boreholes situated close to an industrial area. Most of the people dependent on the boreholes are between 20 and 30 years old, and young children under the age of 2 years. The size of the population is approximately 20 000 people.

Benzene has been found in the groundwater. Benzene is a colourless liquid with a sweet odour. It evaporates into the air very quickly and dissolves slightly in water. Long-term exposure to high levels of benzene in the air can cause leukaemia, cancer of the blood-forming organs. Breathing very high levels of benzene can result in death, while high levels can cause drowsiness, dizziness, rapid heart rate, headaches, tremors, confusion, and unconsciousness. Eating or drinking foods containing high levels of benzene can cause vomiting, irritation of the stomach, dizziness, sleepiness, convulsions, rapid heart rate, and death. It is clear that benzene is both a carcinogen and a toxin.

Two scenarios were calculated: one for the children under the age of 2 years and one for adults between the ages of 20 and 30 years. The results of both assessments produce a risk of 99%.

Table 6.4: Membership functions/values for the intermediate and comprehensive health risk assessment

<table>
<tr><th colspan="4">Membership Functions[1]</th></tr>
<tr><th colspan="2">Radiation[2]</th><th colspan="2">Carcinogen[3]</th></tr>
<tr><td colspan="2">


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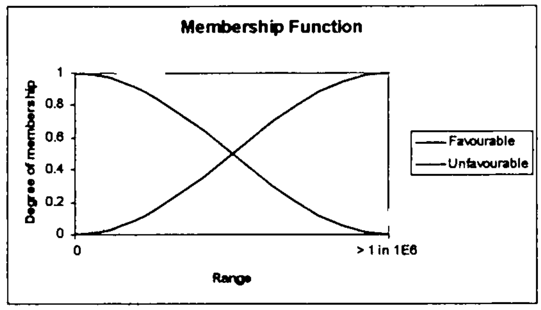
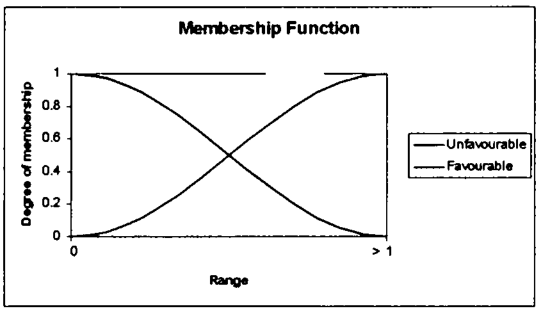
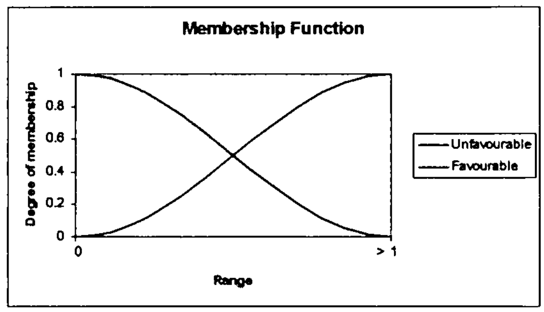
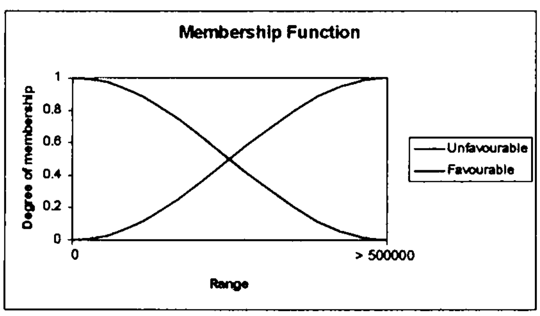


</td></tr>
<tr><th>Unfavourable limit</th><th>Favourable limit</th><th>Unfavourable limit</th><th>Favourable limit</th></tr>
<tr><td>1 in 10^2 - 10^3</td><td>> 1 in 10^6</td><td>1 in 10^2 - 10^3</td><td>>1 in 10^6</td></tr>
<tr><th colspan="2">Infection</th><th colspan="2">Toxin</th></tr>
<tr><td colspan="2">


</td><td colspan="2">


</td></tr>
<tr><th>Unfavourable limit</th><th>Favourable limit</th><th>Unfavourable limit</th><th>Favourable limit</th></tr>
<tr><td>≥1</td><td>< 0.2</td><td>≥1</td><td>< 0.2</td></tr>
<tr><th colspan="4">Size of exposed population</th></tr>
<tr><td colspan="4">


</td></tr>
<tr><th colspan="2">Unfavourable limit</th><th colspan="2">Favourable limit</th></tr>
<tr><td colspan="2">> 500000</td><td colspan="2">< 5000</td></tr>
</table>

[1]Membership functions are documented in Appendix C, Section C8.

[2]1 in 10^x means one person out of every 10^x people exposed has the chance of developing cancer or dying from cancer depending on morbidity or mortality risk respectively.

[3]1 in 10^x means one person out of every 10^x people exposed has the chance of developing cancer.

Figure 6-2 shows the input screen and results of one of the scenarios. It must be noted that in the rapid health risk assessment the user can only select one toxin, one microbiological agent and one carcinogen.

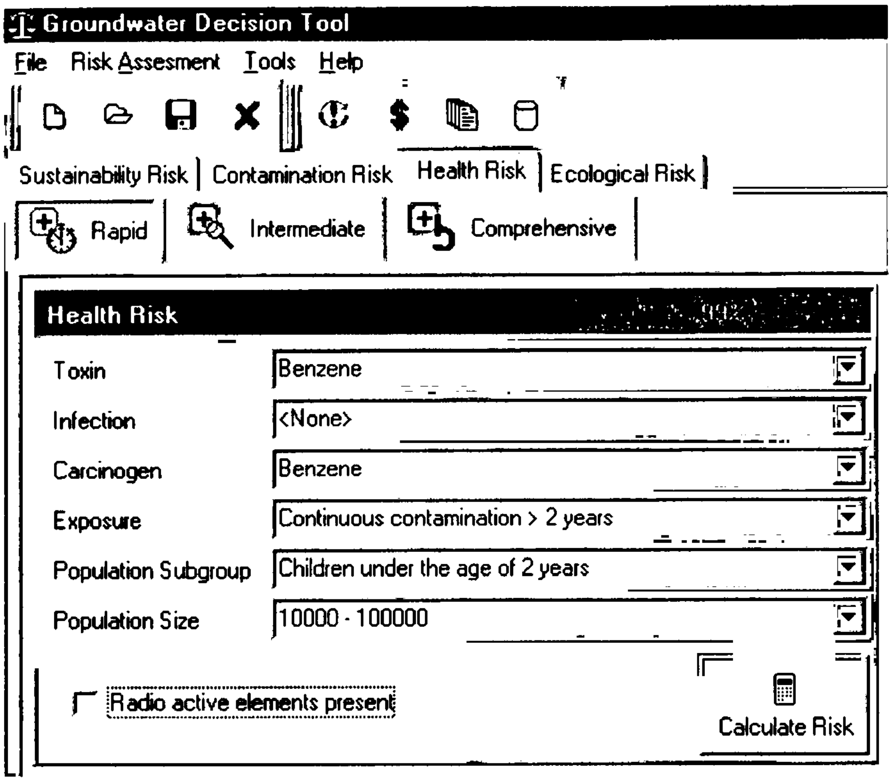


Figure 6-2. Results of rapid health risk assessment

The intermediate and comprehensive assessments are similar. Therefore, only an example of an intermediate risk will be conducted here. Take for example a hypothetical water supply borehole once again situated close to an industrial area. Analyses of the groundwater indicates the presence of hexachlorobenzene. Hexachlorobenzene was widely used as a pesticide to protect the seeds of onions, sorghum, wheat, and other grains against fungus until 1965. It was also used to make fireworks, ammunition, and synthetic rubber. Studies in animals show that eating hexachlorobenzene for a long time can damage the liver, thyroid, nervous system, bones, kidneys, blood, and immune and endocrine systems. The immune system of rats that breathed hexachlorobenzene for a few weeks was harmed. There is no strong evidence that it causes cancer in people.

In addition there are many pit latrines in the area. Further analyses of the groundwater indicate that *Shigella dysenteriae* is also present. *Shigella dysenteriae* causes acute disease of the large and small intestine, diarrhea, fever, nausea, and sometimes toxemia, vomiting, cramps and tenesmus. The infections have up to a 20% fatality rate in hospitalised patients. A person can be exposed to *Shigella dysenteriae by* direct or indirect fecal-oral transmission from a patient or carrier.

Poor hygiene practices spread infection to people by direct physical contact or indirectly by contaminating food and water.

The data used for the risk assessment are listed in Table 6.5. The results of the risk assessment can be seen in Figure 6-3.

Table 6.5: Data required for an intermediate health risk assessment

Data Required	Value
Exposure pathway	Ingestion
Population size	10 000 – 100 000
Carcinogen • Concentration (mg/L)	Hexachlorobenzene 0.03
Toxin • Concentration (mg/L)	Hexachlorobenzene 0.03
Radiation	-
Micro-organism • Number of organisms	Shigella dysenteriae 200
Exposure duration (days)	360

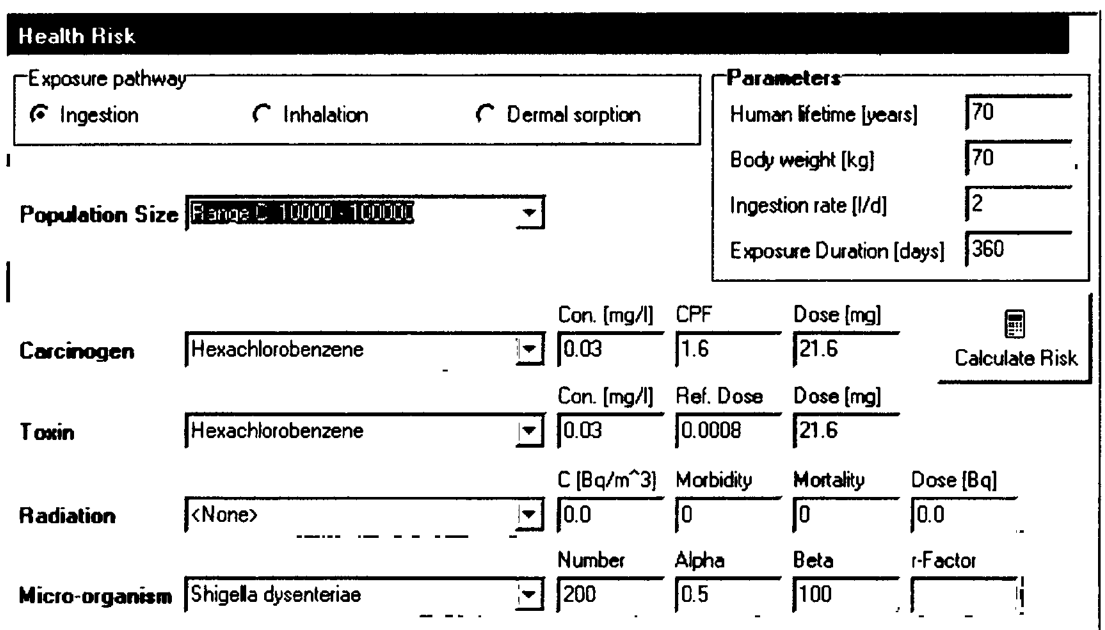


Figure 6-3. Results of intermediate health risk assessment

For a comprehensive assessment the user can choose more than one carcinogen, toxin, radioactive element and micro-organism. The DT will work out the risk taking all selected hazardous elements into account. The exact size of the population under consideration must also be provided.

Chapter 7

Ecological Risk Assessment

7.1 INTRODUCTION

7.1.1 Preamble

The South African National Water Act (Act No 36, 1998) is based on a number of principles one of which is: *the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems* (Scott and Le Maitre, 1998). The Water Act does however focus on aquatic ecosystems and therefore this Chapter will focus on the risk of negative impacts of groundwater (quantity and quality) on aquatic ecosystems.

Aquatic ecosystems are defined as the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs, lakes and wetlands and their fringing vegetation (DWAF, 1996).

Ecological risk assessments differ from health risk assessments in several significant ways. For ecosystems, the risk assessment methodology must consider effects beyond just individual organisms or a single species. No set of ecological values and tolerances applies to all of the various types of ecosystems. With ecosystems some sites and types are more valuable and vulnerable than others. Accommodating these factors complicates ecological risk assessments and renders them more subjective. Unfortunately, there are limited data available concerning South African aquatic ecosystems. This investigation will therefore only consider factors such as groundwater-surface water interactions, groundwater-vegetation dependence, the uniqueness of the ecosystem, groundwater base flow versus abstraction and South African water quality guidelines. These will be used as indicators of the health of the entire aquatic ecosystem. A summary of the general steps in a ecological risk assessment is shown in Figure 7-1.

Groundwater ecological risk assessment

GROUNDWATER QUANTITY

Problem formulation

Establishes the impacts of groundwater on ecosystems taking into account (1) difference between groundwater levels and root depth, (2) type of dependence, (3) surface-groundwater interactions, (4) the groundwater component of base flow and (5) the uniqueness of the ecosystem.

If there is no interaction between groundwater and surface water both the groundwater quantity and quality assessments can be abandoned.

⬇

Analysis

Determine groundwater-surface water interactions (including base flow), determine dependence of vegetation on groundwater.

Estimate the depths of root systems for vegetation. Determine the amount of water needed to sustain vegetation. Take into account the uniqueness of the ecosystems under investigation.

GROUNDWATER QUALITY

Problem formulation

Establishes whether groundwater quality has an impact on ecosystems and if so, what the impact is. If there is no impact the assessment can be abandoned.

Questions to be asked: Does groundwater quality have an impact on ecosystems? If so what is the impact of groundwater quality on ecosystems?

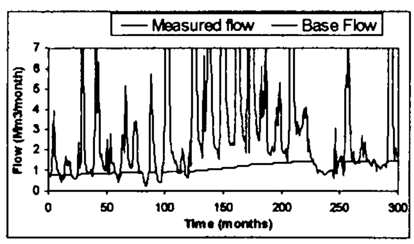
⬇

Analysis

Estimate the water quality required for aquatic ecosystems.

Determine the quality of groundwater.

Determine the impact of changes in groundwater quality on ecosystems taking into account the frequency and duration of changes.



Risk characterisation

Provides an indication of the risks as a result of changes in groundwater levels or quality on ecosystems under the conditions discussed under analysis.

Questions to be asked: What is the nature and likelihood of groundwater impacting ecosystems? How severe are the anticipated adverse effects? What scientific evidence supports the conclusions about the risk?

Figure 7-1. Diagram summarising the ecological risk assessment methodology

7.1.2 Aspects taken into account when determining ecological risks

7.1.2.1 Groundwater-surface water interactions

The first and important aspect to take into account is groundwater-surface water interaction. This has to be determined in order to determine if groundwater plays a role in the sustainability of the aquatic ecosystem under investigation. Scott and Le Maitre (1998) define a number of types of interactions between groundwater and surface water. These are summarised into the following broad categories:

- Influent: The groundwater level is lower than the surface water level, and therefore surface water is recharging groundwater.
- Effluent: The groundwater level is higher than surface water level, and therefore groundwater is recharging surface water.
- Intermittent: The groundwater level is higher than the bed of the surface water body, but depending on the elevation of the water level, groundwater may recharge the surface water body or the surface water may recharge groundwater.
- Detached: The groundwater level is below the surface water level and the two do not influence each other.

These interactions are depicted in Figure 7-2. If the surface water body and the groundwater system are detached or the surface water body is influent then the ecological risks due to groundwater are zero.

The amount of base flow from groundwater entering a surface water body has direct impacts on the aquatic ecosystems present in and surrounding the water body.

7.1.2.2 Dependency of vegetation on groundwater

The degree of dependence of vegetation on groundwater as a source of water and survival is important when determining ecological risks. The dependency on groundwater can be classified as (Scott and Le Maitre, 1998):

- Obligatory phreatophytes obtain their water supply from the saturated zone and are most vulnerable to impacts caused by groundwater exploitation, or some other case of reduced groundwater levels. These phreatophytes can be sub-divided according to Hatton and Evans (1998) into the following classes:

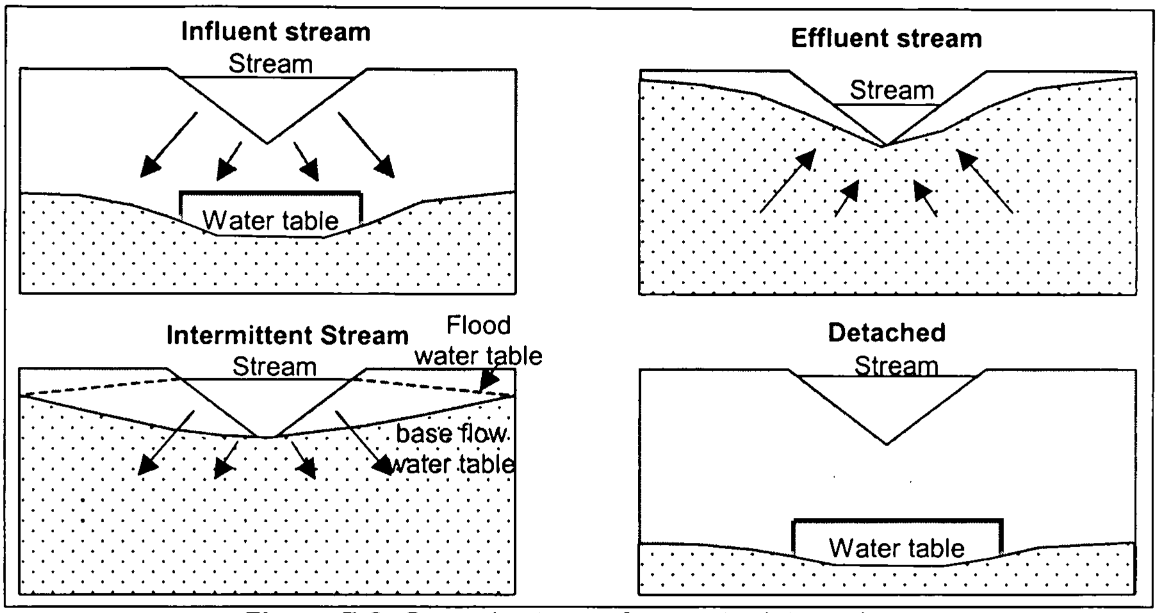


Figure 7-2. Groundwater-surface water interactions

- Entirely – The ecosystem is entirely dependent on groundwater, and were groundwater to diminish or be modified only slightly, either below a threshold like the ground surface or such that a surface water body stops flowing, the ecosystem will be destroyed. Examples of such ecosystems can be related to springs, permanent lakes and groundwater discharges into the saline bodies such as the sea.
- Highly – Moderate changes to groundwater discharge or water tables would lead to substantial decreases in the extent and health of the ecosystem. An example of such an ecosystem is a swamp.
- Proportionally – For a number of systems it is likely that a unit change in the amount of groundwater will result in a proportional change in the health of that ecosystem. In other words, if the groundwater discharge is halved, one might expect the same diminution of the ecosystem. An example of such an ecosystem can be the river plains of a perennial river.

- Facultative phreatophytes exploit groundwater without being dependent on it for survival.
- Vegetation that is not dependent on groundwater.

7.1.2.3 Depth of root system

The depths of plant root systems are highly variable and systematic studies are rare. Although deep roots may only comprise a small fraction of the rooting system they may be critical for plant survival, a few deep roots can even sustain large trees. Studies of diurnal and seasonal water relations show that species able to maintain root systems in contact with groundwater tables have high transpiration rates and show little seasonal variation in water stress (Scott and Le Maitre, 1998).

7.1.2.4 Uniqueness of ecosystem

The seriousness of ecological risks does not only depend on the hazard but also the uniqueness of the ecosystem being affected. Ecosystems are therefore classified according to endangered, sensitive indigenous, indigenous and alien species. Even though the uniqueness of the system will be impacted by both water quantity and quality changes, for the sake of convenience, it will be included in the quantity assessment.

7.1.2.5 Change in water quality

Change in groundwater quantities and groundwater contamination can have a direct impact on aquatic ecosystems. The changes in water quality can cause the following (DWAF, 1996):

- Chronic effects – This is defined as that concentration or level of a constituent at which there is expected to be a significant probability of measurable chronic effects in up to 5% of species in the aquatic ecosystem.
- Acute effects – This is defined as that concentration or level of a constituent above which there is expected to be a significant probability of acute toxic effects in up to 5% of the species in the aquatic ecosystem. If an acute effect persists for even a short while, or occurs at too high a frequency, it can quickly cause the disappearance of sensitive species.

According to the South African Water Quality Guidelines (DWAF, 1996) there are 4 categories of constituents that effect aquatic ecosystems:

- Toxic constituents – Seldom occur in high concentrations in unimpacted systems. Examples are inorganics (Al, As, Cd, Cu F^-, Hg, Mn and NH_4^+) and organics (phenol and atrazine).
- System variables (for example pH) – Regulate essential ecosystem processes such as spawning and migration. Changes in the amplitude, frequency and duration of natural seasonal cycles may cause severe disruptions to ecological and physiological functions of organisms.
- Non-toxic inorganic constituents – May cause toxic effects at extreme concentrations, for example total dissolved solids (TDS) and total suspended solids (TSS).

- Nutrients – Are generally not toxic, but can stimulate eutrophication if present in excessive quantities.

7.1.2.6 Duration of exposure to contamination

If the contamination is a once-off spill the impacts will most probably be smaller than those of a continuous source.

7.2 DATA REQUIREMENTS

As with all risk assessments, a fuzzy logic system will be used to determine the ecological risks. The fuzzy rules will remain the same for all tiers of the risk assessment, however the quality of data as well as methods used to determine groundwater base flow vary. Table 7.1 and Table 7.2 is a summary of the data requirements and potential data sources.

Table 7.1: Data required for the quantity ecological risk assessment and potential data sources

Data required	Potential data sources		
	Rapid	**Intermediate**	**Comprehensive**
Water quantity			
Perennial/Non-perennial	User	User or DT	User
Groundwater level	User to estimate	User from field data	User from field data
Vegetation type to determine root depth	User to give vegetation type corresponding root depths in DT database[1]	User to give vegetation type corresponding root depths in DT database[1]	User from field data
Groundwater-surface water interaction	User from DT database[2]	User from field data	User from field data
Type of dependence	User	User	User to determine from field data
Groundwater component of base flow • Primary catchment • Quaternary catchment • Total monthly flows • In flow stream requirements	 User[3] - -	 - User[4] -	 - User User
Influence of abstraction on groundwater base flow • Abstraction rate in borehole(s)[5]	User	User	User
Uniqueness of ecosystem	User	User	User

[1]See Appendix D, Section D1. [2]See Appendix D, Section D2. [3]See Appendix D, Section D3. [4]See Appendix D, Section D4. [5]Only one borehole is included in the rapid assessment.

Table 7.2: Data required for the quality ecological risk assessment and potential data sources

Data required	Potential data sources		
	Rapid	**Intermediate**	**Comprehensive**
Water quality			
Toxin • Aquatic ecosystem guidelines • Concentration • Injection rate • Duration of injection	User DT database[1] - - User[2]	User DT database[1] Laboratory analyses - User[2]	User DT database[1] Laboratory analyses User User[2]
Hydraulic conductivity • Aquifer type	- -	User OR DT database[3]	User
Porosity • Aquifer type	- -	User OR DT database[4]	
Groundwater gradient	-	User	User[5]
Dispersivity • Borehole position, concentration & time	- -	User[6] -	User[7] User[7]
Source • Source position • Distance between source and riparian zone	- -	- User	User User
Evaluation time	-	User	User

[1]See Appendix D, Section D6 [2]See Table 7.4.
[3]See Appendix B, Section B7 [4]See Appendix B, Section B8.
[5]Can use Tripol software to calculate groundwater gradient.
[6]User to enter dispersivity value or the DT will use the distance between source and riparian zone to calculate dispersivity.
[7]User to enter dispersivity value or user can enter a borehole position, concentration and time. The DT will then calculate dispersivity.

7.3 ASSUMPTIONS AND LIMITATIONS

Rapid Assessment

- Only abstraction borehole closest to the aquatic ecosystem is taken into account.
- Literature, maps, rules of thumb and elementary calculations are used to determine the membership functions and decision rules.
- Does not take concentrations into consideration.

Intermediate Assessment

- When calculating the concentration of contamination at any point in the aquifer only advective-dispersive processes are taken into account.

Comprehensive Assessment

- When calculating the concentration of contamination at any point in the aquifer only advective-dispersive processes are taken into account. The source can however be a slug or a continuous source.

General – applicable to all assessments

- Surface water levels and flow conditions in surface water bodies are not taken into account.
- In many cases it is necessary for an ecosystem to experience some stress. However, reducing the availability of groundwater too much may result in a gradual decrease in the health of the ecosystem. On the other hand, an abundance of groundwater can also be harmful to ecosystems. For example the roots of certain plants can be drowned. These changes in groundwater levels are not taken into account in the DT.
- Fish and other invertebrates are indirectly taken into account by applying aquatic ecosystem guidelines and considering the groundwater component of base flow.
- If a river is non-perennial it is assumed that all risks are zero.
- Only toxic constituents will be taken in account in the risk assessment process. However other factors (such as system variables and nutrients) will be discussed and taken into account in protecting and remediating a resource. This will be discussed in more detail in Chapter 8.
- The distance of a borehole from a surface water body is not taken into account.

7.4 METHODOLOGY

The methodology to assess the ecological risk is the same as discussed in Section 3.2. Therefore, it is once again necessary to set up decision rules and membership functions, which are the same for all tiers of the assessment. These rules and functions have been discussed with Gerrit van Tonder (Institute for Groundwater Studies), Christine Colvin (CSIR) and Dave Le Maitre (CSIR) all of whom have conducted research on ecosystem-groundwater interactions. The quality of data and calculations for the various tiers of assessments differ. The calculations needed for the risk assessment are summarised in Table 7.3. The membership functions for the decision rules are documented in Table 7.4.

Table 7.3: Calculations for aquatic ecosystems risk assessment

QUANTITY ASSESSMENT			
Data required	**Rapid Assessment**	**Intermediate Assessment**	**Comprehensive Assessment**
The following is required to determine base flow: • The primary catchment for the rapid assessment. • The quaternary catchment for the intermediate assessment. • Total monthly flow and inflow stream requirements (IFRs) for the comprehensive assessment. The base flow value (and IFR) is compared to the amount of groundwater being abstracted (see Table 7.3). *It is important to note that if the percentage noflow is not equal to zero then there are no impacts of groundwater on aquatic ecosystems and the risk is zero.*	The natural base flow is determined from the Vegter and Pitman (1996) primary catchment values (See Appendix D, Section D3). Only one abstraction borehole is taken into account	The base flow is determined using the SARES program by Hughes (1999). See Appendix D, Section D4. All abstraction boreholes are taken into account.	Base flow must be determined using one of the existing methodologies for example Van Tonder (2001). All abstraction boreholes are taken into account.
To estimate the depths of root systems the following data are needed: • Types of vegetation for the rapid and intermediate assessments. • Depths of root system from field investigations for comprehensive assessment. The water table in the riparian zone is compared to the root depths. If there is more than a 2 m difference it is accepted that the vegetation under investigation is not dependent on groundwater, if there is less than 0.5 m difference it is accepted that the vegetation is totally dependent on groundwater.	The vegetation type is used to estimate the average root depth (See Appendix D, Section D1).	The vegetation type is used to estimate the average root depth (See Appendix D, Section D1). OR The user can enter the root depth.	A field investigation is necessary to determine the types of plants potentially dependent on groundwater together with their associated root depths.

Table 7.3 continued

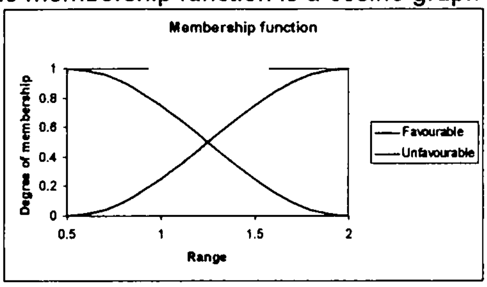
QUALITY ASSESSMENT			
Data required	**Rapid Assessment**	**Intermediate Assessment**	**Comprehensive Assessment**
The maximum concentration at the boundary of the riparian zone is calculated and compared to the South African aquatic ecosystem water quality guidelines (See Appendix D, Section D6). The data required for the calculations are: No information is needed for the rapid assessment. For the intermediate assessment the following is needed: • Initial concentration at the source (C_0). • Length between riparian zone and source (L). This is also used to calculate the dispersivity value (α) • Duration of contamination (t). • Groundwater gradient (dh/dl), effective porosity (n_e) and hydraulic conductivity (K) to determine velocity (v). • Dispersivity (α) and velocity (v) to determine the dispersion coefficient (D). For the comprehensive assessment the following is needed: • Initial concentration at the source. • Positions of source and boreholes. • Duration of and injection rate of contaminant. • Area of source and thickness of aquifer. • Groundwater gradient, effective porosity and hydraulic conductivity to determine velocity. • Dispersion coefficients. • Concentration at point in aquifer together with coordinates of point and time at which concentration was measured.	No concentration values are needed and no calculations are performed. Refer to Table 7.4.	The equation used to calculate concentrations is in the following format (Fetter, 1999): $C = \frac{C_0}{2}\left[\text{erfc}\left(\frac{L - vt}{2\sqrt{Dt}}\right)\right]$ where $D = \alpha v$ and $v = \frac{K}{n_e}\left(\frac{dh}{dl}\right)$.	Two calculations will be used for the following contamination sources: • Continuous injection • Slug (once-off) injection. For information concerning the Equations used in this section refer to Appendix B (Section B5). It is important to note that dispersion coefficients must be determined by means the equations in Appendix B (Section B5).

Table 7.4: Membership functions/values for decision rules for ecological risk assessment

WATER QUANTITY ASSESSMENT[1]

Difference between groundwater level (mbgl) and root depth (m)

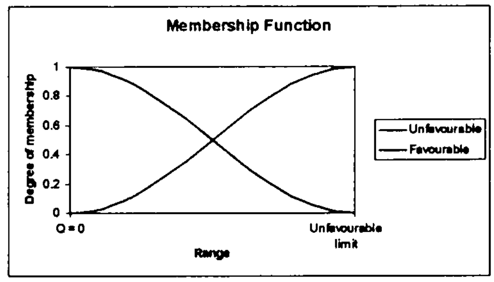
The membership function is a cosine graph



Unfavourable limit	Favourable limit
≤ 0.5	2

Base flow (BF) versus abstraction (Q)

The membership function is a cosine graph



Unfavourable limit	Favourable limit
$Q \geq 0.3$ BF[3] $Q \geq 0.2$ BF[4] $Q \geq$ BF – IFR[5]	Q = 0

Type of dependence

Range	Membership value
Obligatory: Entirely	0.0
Obligatory: Highly	0.2
Obligatory: Proportionally	0.4
Facultative	0.8

Surface water – groundwater interaction

Range	Membership value
Effluent	0.0
Intermittent	0.2
Influent	1.0
Detached	1.0

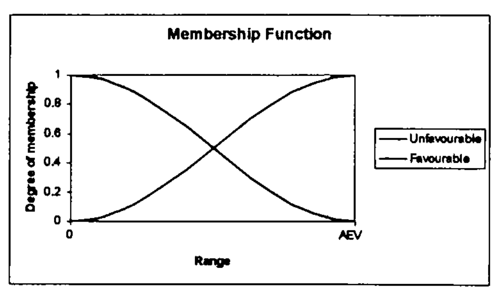
Uniqueness of ecosystem

Range	Membership
Endangered	0.0
Sensitive indigenous	0.2
Indigenous	0.5
Alien	1.0

WATER QUALITY ASSESSMENT

Toxins[2]

Unfavourable limit	Favourable limit
Acute effect value (AEV)	0



Duration of contamination

Range	Membership value
Contamination may be seconds, minutes or hours	0.9
Contamination occurs at intermittent periods < 2 years	0.6
Contamination > 90 days and < 2 years	0.6
Contamination occurs at intermittent periods >2 years	0.3
Continuous contamination > 2 years	0.0

[1]Membership functions are documented in Appendix D, Section D5. [2]Refer to Appendix D, Section D6 for Aquatic Water Quality Guidelines. For the rapid assessment, concentrations are not needed therefore the contaminants are classified according to death (1.0), effects common (0.75), long-term effects (0.6) and few effects (0.2). [3]For rapid assessment. [4]For intermediate assessment. [5]For comprehensive assessment inflow stream requirements (IFRs) are needed.

The ecological risks (quantity and quality) are calculated using Equation 3.1. The decision rules on which the calculations are based are listed in Appendix E, Section E5. The overall ecological risk can then be calculated by means of the following Equation:

$$Risk_{ecology} = \max(Risk_{quantity}, Risk_{quality})$$

7.5 EXAMPLE

The Mutshindudi River Catchment, A91G, (Figure 7-3) is located some 50 km east of Louis Trichardt in the Northern Province of South Africa. The study area is underlain mainly by Soutpansberg Group Rocks consisting of the Sibasa Basalt Formation and the Fundudzi Formation. Diabase intrusions are common throughout the study area, occurring as sills and dykes.

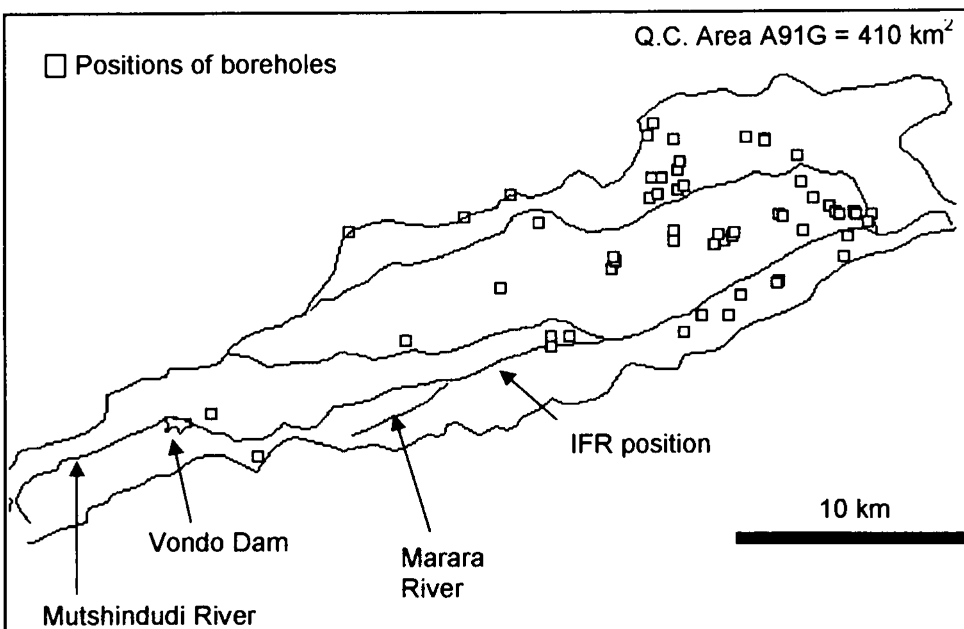


Figure 7-3. The Mutshindudi River Catchment

As the rapid assessment is elementary, and the intermediate and comprehensive assessments are similar, only a comprehensive assessment will be conducted in this example. Where the required data is not available for the comprehensive assessment, hypothetical values are assumed.

The assessment is divided into a quantity and quality assessment. The data required for each are listed in Table 7.5.

Table 7.5: Data required for ecological risk assessment

Input	Value
Quantity Assessment	
Base flow estimation (m^3/s)	0.4170
Inflow stream requirements for the same period as the monthly flow values (m^3/s)	0.275
Perennial/non-perennial	Perennial
Vegetation type to determine average root depth	Trees - overall
Water table (mbgl)	8
Groundwater-surface water interaction	Effluent
Plant dependence on groundwater	Obligatory entirely
Uniqueness of ecosystem	Indigenous
Abstraction rates	BH1 = 5 L/s, BH2 = 5 L/s
Quality Assessment	
Duration of pollution	Polluting > 90 days and < 2 years
Contaminant	Ammonia
Position of source	X = 0, Y = 0
Initial concentration of contaminant (mg/L)	10
Distance between source and riparian zone (m)	500
Area of source (m^2)	1
Dispersivity[1] (m)	70
Hydraulic conductivity (m/d)	6
Porosity	0.1
Groundwater gradient	0.02
Evaluation time (days)	360

[1]Or the user can enter a borehole with coordinates, a concentration value and the time at which the concentration was measured. The DT will then calculate the dispersivity value.

The input screen and results of the quantity risk assessment can be seen in Figure 7-4.

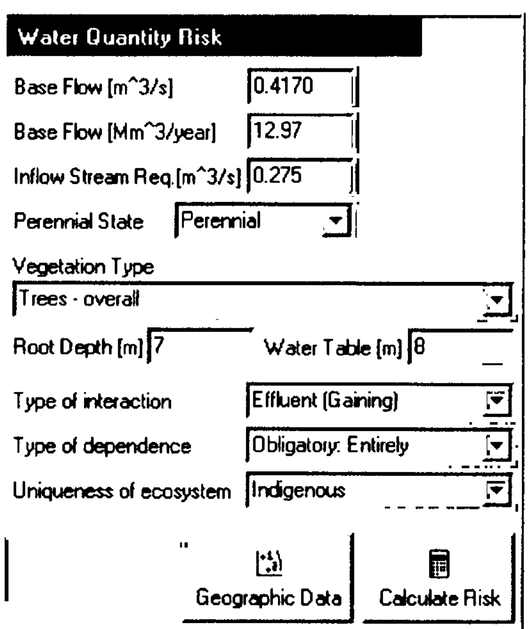


Figure 7-4. Comprehensive quantity risk assessment

The input screen and results of the quality risk assessment are shown in Figure 7-5.

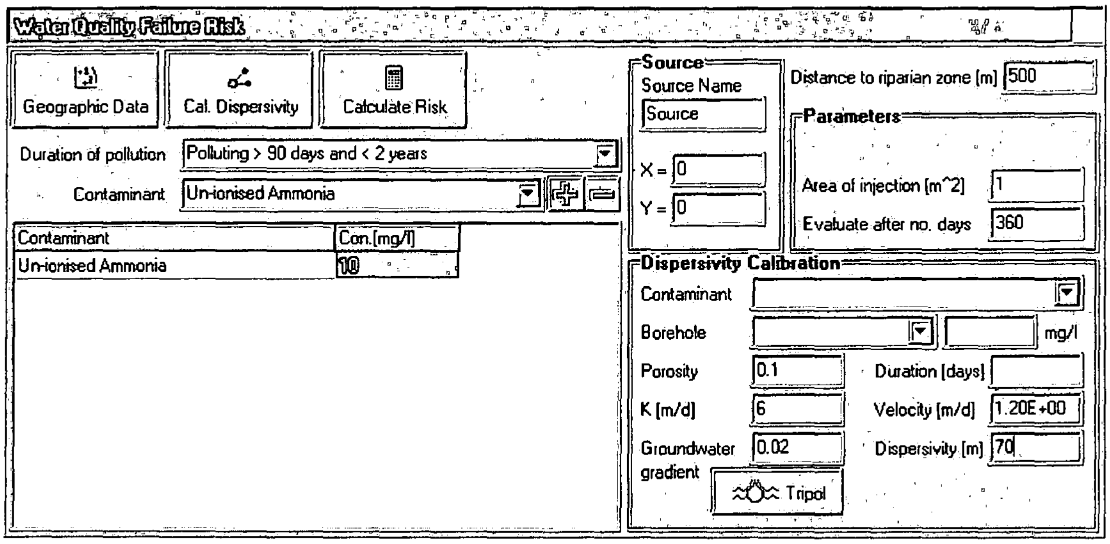


Figure 7-5. Comprehensive quality risk assessment

The total ecological risk can then be calculated as:

$$Risk_{ecology} = \max(Risk_{quantity}, Risk_{quality}) = 87\%$$

An important note: The option polluting > 90 days and < 2 years is treated as a slug source, so once the contaminant has moved passed a certain point in the aquifer the risk will decrease. For example if the distance to the riparian zone is decreased to 10m, then the risk will decrease to 26% as the center of the contaminant has passed that point after a year. However if the time is reduced to 30 days, the risk will increase to 99%, 10m from the source.

Chapter 8

Prevention and Remediation

8.1 INTRODUCTION

Since the early 1980's geohydrologists and engineers have developed a number of techniques for protecting groundwater. The National Water Act (Act No 36, 1998) defines protection in relation to a water resource as:

a) *Maintenance of the quality of the water resource to the extent that the water resource may be used in an ecologically sustainable way;*

b) *Prevention of the degradation of the water resource; and*

c) *The rehabilitation of the water resource.*

It is clear that protection refers to both the quantity and quality of a resource. The government places so much emphasis on protection of water resources that a whole chapter of the National Water Act is dedicated to discussing this topic. In this chapter, it is also clearly stated that protection is divided into two categories: measures to prevent the pollution of water resources, and measures to remedy the effects of pollution on water resources. These two categories will be discussed in more detail in the following sections.

8.2 PREVENTION

According to the National Water Act (Act No 36, 1998), the persons who own, control, occupy or use the land in question are responsible for taking measures to prevent pollution of water resources, and in the context of this thesis, groundwater resources. If these measures are not taken, the catchment management agency concerned may itself do whatever is necessary to prevent the pollution and to recover all reasonable costs from the responsible persons.

There are two major approaches to prevention or minimisation of contamination, namely:

- source control measures and
- groundwater or borehole protection measures.

Each of these will be discussed in more detail in the following sections.

8.2.1 Source Control Measures

The objective of source control is to reduce or eliminate the volume of contamination, thereby eliminating or minimising groundwater pollution. Source control measures include the physical removal or reduction of the source of contamination or the containment of the source. If the source is removed, contamination can no longer migrate from it. It is however important to note that the excavation and removal of hazardous waste materials must be done in a manner that protects the health and safety of the workers and the public. The risk and costs of moving material must be weighed up against the risk and costs of remediation involved to leaving it in place. If the source of contamination cannot be economically or technically removed, then it may be possible to contain it. A groundwater cutoff wall can divert groundwater flow from passing through a contaminant source. If there is no recharge or flow through the cutoff wall, then the water table within the wall will remain flat (see Figure 8-1). However, there is generally leakage through the cover or cutoff walls, so some abstraction boreholes will be needed within the wall to prevent build-up of water within the walls. If the cutoff walls are extended far enough around the source and contaminant plume, then remediation may proceed without concern that it will spread further. In most cases it will also be necessary to construct a cover over the contamination to prevent the infiltration of precipitation. Table 8.1 is a summary of some of the cutoff walls that can be used to contain pollution.

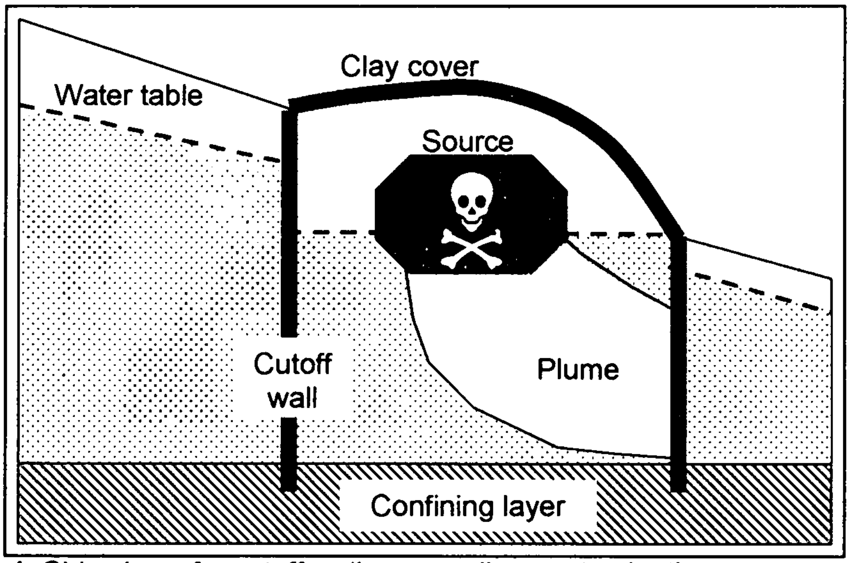


Figure 8-1. Side view of a cutoff wall surrounding contamination source and plume.

Table 8.1: Types of cutoff walls *(Summarised from http://www.clu-in.org/remed1.cfm)*

Type of cutoff wall	Description
Bentonite slurry	These subsurface barriers consist of a vertically excavated trench that is filled with a slurry. The slurry hydraulically shores the trench to prevent collapse and forms a filter cake to reduce groundwater flow. Slurry walls are often used where the waste mass is too large for treatment and where soluble and mobile constituents pose an imminent threat to a source of drinking water. Most slurry walls are constructed of a soil, bentonite, and water mixture; walls of this composition provide a barrier with low permeability and chemical resistance at low cost. Other wall compositions, such as sheet piling, cement, bentonite, and water, may be used if greater structural strength is required or if chemical incompatibilities between bentonite and site contaminants exist. Slurry walls are typically placed at depths less than 15 m and are generally 0.6 to 1.2 m thick. Soil-bentonite backfills are not able to withstand attacks by strong acids, bases, salt solutions, and some organic chemicals.
Cement-based grout	The subsurface barrier technology is a combination of techniques to install and verify the integrity of a barrier. The grouts must have the proper hardening time considering the method of injection. This will ensure the grout does not harden too quickly so that it reaches the areas where it is needed and it does not harden too slowly that it spreads out too thinly. Barriers are limited by the depth and directional control of the drilling technology and limited by the inability of nonintrusive techniques to verify barrier continuity.
Sheet piling	A sheet piling barrier can be made from a variety of materials: wood, recast concrete, and steel. Steel is the most common material because of its high durability, low cost, and high flexibility. Sheet pilings are constructed by driving individual sections of interlocking steel sheets into the ground with impact or vibratory hammers to form an impermeable barrier. The retaining sheet pile walls flex from water or lateral earth pressure applied to them. The flexure tightens the interlocks making the connection more water resistant. The process is not suitable for stiff clay or soils containing cobbles and boulders.
Synthetic membranes	Synthetic membranes used for vertical cutoff walls are generally made from high-density polyethylene; however, other polymers have been used. Membrane sheets can be continuous, but usually finite length panels that interlock are preferred.

8.2.2 Protection of a groundwater resource

Groundwater for basic human needs and aquatic ecosystems need to be protected, the most important being water for basic human needs. This section will therefore focus on the protection of groundwater (quantity and quality) for basic human needs, and aquatic ecosystems.

8.2.2.1 Protection of basic human needs boreholes and springs

The parameter that should be considered when determining a protection area around a borehole is the capture area of the borehole which will be used to estimate its safe yield and to determine the impact of pollution (Van Tonder and Dennis, 2000).

A capture area or zone is defined as the area contributing flow to that particular borehole. If the groundwater heads are flat, the capture zone is radially symmetrical, centered on the borehole and extending as far as the cone of depression. However, if there is a slope in the groundwater heads, there is regional groundwater flow and the capture zone is asymmetrical, with the greatest extent in the up-gradient direction. The shape of the capture zone is a function of the average linear groundwater velocity, the quantity of water being pumped from the aquifer, and the distribution of hydraulic conductivity. The up-gradient extent of the capture zone depends on the length of time over which the pumping occurs (Fetter, 1999). Traditionally numerical models have been used to determine capture zones. However there may not always be sufficient data to use this methodology. Therefore if there is insufficient data available, wellhead protection areas (WHPAs) need to be delineated. A WHPA can be defined as the surface and subsurface area surrounding a borehole or wellfield, supplying basic human needs, through which contaminants are reasonably likely to move and reach such a borehole or well field. In many cases it is difficult to protect the whole area, therefore various zones are established within the area. These zones are defined and discussed in Table 8.2.

Table 8.2: Zones within WHPA *(Summarised from Braune, 2000; EPA, 2001 and Boulding, 1995)*

Zone	Definition	Constraints	Calculation
Zone 1: Accident prevention or sanitary protection.	Highly protected area around the borehole or spring. Its purpose is to protect the borehole or spring from the direct introduction of contaminants into the borehole and its immediate area from spills, surface runoff, or leakage from storage facilities or containers. Potential contaminant sources in Zone 1 should be strictly monitored.	Vehicle and pedestrian traffic, Agriculture, All constraints of zone 2 & 3.	Determine 50 day travel time: $$r_{50} = \frac{50K\frac{dh}{dl}}{n_e}$$ where K = hydraulic conductivity, dh/dl = groundwater gradient and n_e = effective porosity[1]. In the case of a fractured rock system, the porosity must reflect the nature of the system. This can be determined from tracer tests discussed in Chapter 2, Section 2.3.3.
Zone 2: Attenuation	Is established to protect a borehole from contact with pathogenic micro-organisms (e.g. bacteria and viruses) which can emanate from a source (eg septic system) located close to the borehole, as well as to provide emergency response time to begin active cleanup and/or implementation of contingency plans should a chemical contaminant be introduced into the aquifer near the borehole.	Workshops, Farm stables and sheds, Stockyards of building material, Roads and railways, Parking lots, Car washes, Cemeteries, Mining, Fuel storage, Small informal settlements with pit latrines, Junk yards, All constraints of zone 3.	2 year TOT[2] radius area. The radius is calculated as: $$r_{TOT} = SF\sqrt{\frac{Qt}{n_e D\pi}}$$ where Q = Annual average pumping rate, n_e = effective porosity[1], D = saturated thickness of aquifer, t = 2 years time of travel and SF = safety factor (=1.3 when all values are known, = 1.5 when there are some unknowns). In the case of a fractured rock system, the porosity must reflect the nature of the system. This can be determined from tracer tests discussed in Chapter 2, Section 2.3.3.

Table 8.2 continued

Zone 3: Remedial action	Is designed to protect the borehole from chemical contaminants that may migrate to the borehole; it typically includes a major portion of the recharge area or the capture zone.	Mass livestock, Wastewater and sewage treatment, Hospitals, Airports and military facilities, Trucking and bus facilities, Waste sites, Oil refineries, Chemical plants and nuclear reactors, Deposition and underground storage of water-endangering substances, Pipelines for water-endangering substances, Large informal settlements using pit latrines, Dry cleaning establishments.	5 year TOT radius. The radius is calculated as: $r_{TOT} = SF\sqrt{\frac{Qt}{n_e D\pi}}$ where Q = Annual average pumping rate, n_e = effective porosity[1] D = saturated thickness of the aquifer, t = 5 years time of travel and SF = safety factor (=1.3 when all values are known, = 1.5 when there are some unknowns). In the case of a spring determine radius of influence with t = memory time of the spring. In the case of a fractured rock system, the porosity must reflect the nature of the system. This can be determined from tracer tests discussed in Chapter 2, Section 2.3.3.

[1]If effective porosity is not known the user can use values stored in the DT database. Refer to Appendix B, Section B8.
[2]The TOT criterion bases WHPA delineations on the amount of time it takes groundwater to travel from a point source to a borehole.

8.2.2.2 Protection of groundwater for aquatic ecosystems

When protecting aquatic ecosystems the user has to consider both the groundwater gradient towards the aquatic ecosystem and the quality of this water. The protection is therefore divided into protecting quantity and quality.

Protection of groundwater flow towards an aquatic ecosystem

The protection of groundwater flow towards an aquatic ecosystem is based on the assumption that the groundwater gradient in and around the riparian zone must be able to maintain the requirements of the system. These requirements are known as inflow stream requirements (IFRs) and are set by a team of specialists. If however the IFRs are not known the user can assume that 20% of base flow is necessary to maintain aquatic ecosystems (this value has been obtained from numerous field investigations). In addition the groundwater flow toward an ecosystem will vary from month to month and these variations are usually necessary to maintain the optimal functioning of the ecosystems. It is suggested that the user base the calculations of the groundwater gradient required to maintain the aquatic ecosystem on a high flow and a low flow determination. It would be more accurate to calculate the gradient for every month of the year. The methodologies included in the DT are listed in Table 8.3.

Protection of groundwater quality flowing towards an aquatic ecosystem

There are two methods to protect the groundwater quality flowing toward an aquatic ecosystem, the first being a protection zone around the aquatic ecosystem and the second being a number of constraints on system variables, non-toxic inorganic constituents and nutrients as defined in Chapter 7, Section 7.1. The protection zones and constraints are discussed in more detail in Table 8.3.

Points to consider when protecting groundwater for aquatic ecosystems:

- The protection areas delineated in this section are for ideal conditions, where basic human needs are not an issue. However, when these and other factors become important, the size of the protection area can be changed.
- The surface water body is assumed to be dependent on groundwater.

Table 8.3: Protection of aquatic ecosystems

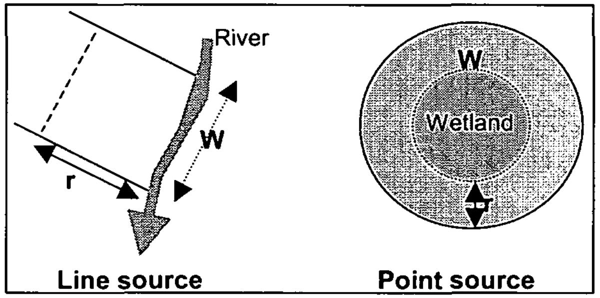
QUANTITY OF GROUNDWATER FLOWING TOWARD THE AQUATIC ECOSYSTEM	
Data required	**Method**
• Groundwater component of base flow (BF) or IFR. • Transmissivity (T). • Length of surface water body under investigation (W).	The groundwater gradient that must be maintained is: $i = \frac{QB \times 0.8}{TW}$ or if the IFR is known $i = \frac{IFR}{TW}$ In the case of a fractured rock system, the transmissivity must reflect the nature of the system.
QUALITY OF GROUNDWATER FLOWING TOWARD THE AQUATIC ECOSYSTEM	
Data required	**Method**
Protection area/zone • Groundwater component of base flow (BF). • Effective porosity (n_e). • Saturated aquifer thickness (D). • Safety factor (SF) (=1.3 when all values are known, = 1.5 when there are some unknowns).	The length r of the protection area is calculated as: $r = SF\sqrt{\frac{2BF}{n_e D \pi}}$ In the case of a fractured rock system, the porosity must reflect the nature of the system. This can be determined from tracer tests discussed in Chapter 2, Section 2.3.3. 

Table 8.3 continued

Constraints taken from South African Water Quality Guidelines (DWAF, 1996).	**1. System variables** Dissolved oxygen: Must not drop below the arithmetic mean of the daily minimum instantaneous concentrations measured at hourly intervals over 7 consecutive days AND the lowest instantaneous concentration recorded in a 24-hour cycle, or the instantaneous concentration at sunrise. Target value 80 – 120% of saturation concentration. pH: The pH values should not be allowed to vary from the range of the background pH values for a specific site and time of day, by > 0.5 of a pH unit OR by > 5%, and should be assessed by whichever estimate is more conservative. Temperature: Water temperature should not be allowed to vary from the background average daily water temperature considered to be normal for that specific site and time of day, by > 2°C OR by > 10%, whichever estimate is more conservative. **2. Non-toxic constituents** Total dissolved solids (TDS): TDS concentrations should not be changed by > 15% from the normal cycles of the water body under unimpacted conditions at any time of the year AND the amplitude and frequency of natural cycles in TDS concentrations should not be changed. Total suspended solids (TSS): Any increase in TSS concentrations must be to < 10% of the background TSS concentrations at a specific site and time. **3. Nutrients** Nitrogen: The inorganic nitrogen concentrations should not be changed by more than 15% of unimpacted conditions at any time of the year AND the trophic status of the surface water body should not increase above its present level AND the amplitude and frequency of natural cycles in inorganic nitrogen concentrations should not be changed. Phosphorus: The inorganic phosphorus concentrations should not be changed by > 15% from unimpacted conditions at any time of the year AND the trophic status of the water body should not increase above its present level AND the amplitude and frequency of natural cycles in inorganic phosphorus concentrations should not be changed. **4. Toxic constituents** The concentrations of none of the toxic nutrients may exceed the chronic effect value as documented in the Water Quality Guidelines for Aquatic Ecosystems.

8.2.3 Examples

When selecting the remediation and protection screen appears (Figure 8-2). By selecting "Borehole Protection", the screen appears where the values can be entered to calculate the various protection zones as discussed in Table 8.2. The definition of each zone together with the constraints appears on the left-hand side of the screen. When selecting "Geographic Data" the boreholes under consideration can be entered. The DT will then tell the user in which assessments the required data has been used under the "mapping" boxes. The user can then decide which assessment's data to use for these calculations. The user can also enter the data directly in the table provided.

Take for example borehole UO5 situated at the Campus Site of the University of the Free State. The data have directly been entered into the table (Figure 8-3). The radius of the protection zones then appears after "Calculate Zones" has been selected. By selecting "Geographic Data" the user can view the zones (Figure 8-4).

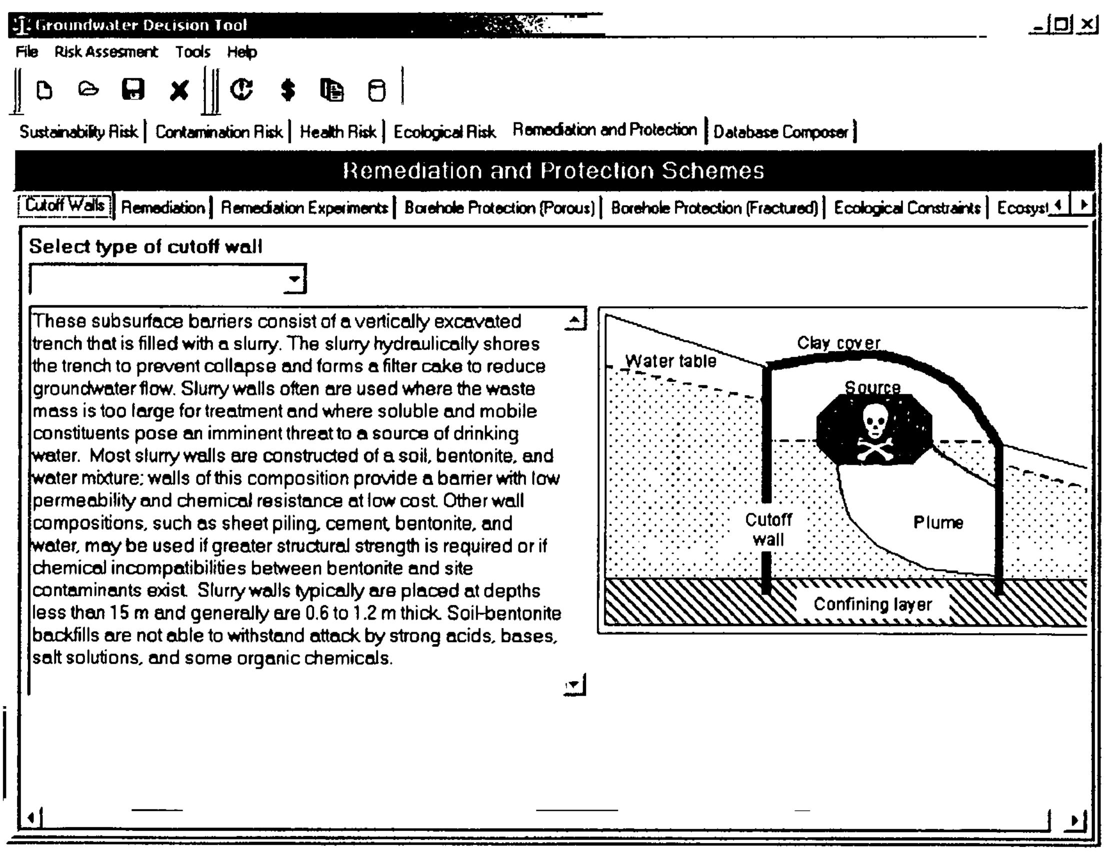


Figure 8-2. Initial remediation and protection screen

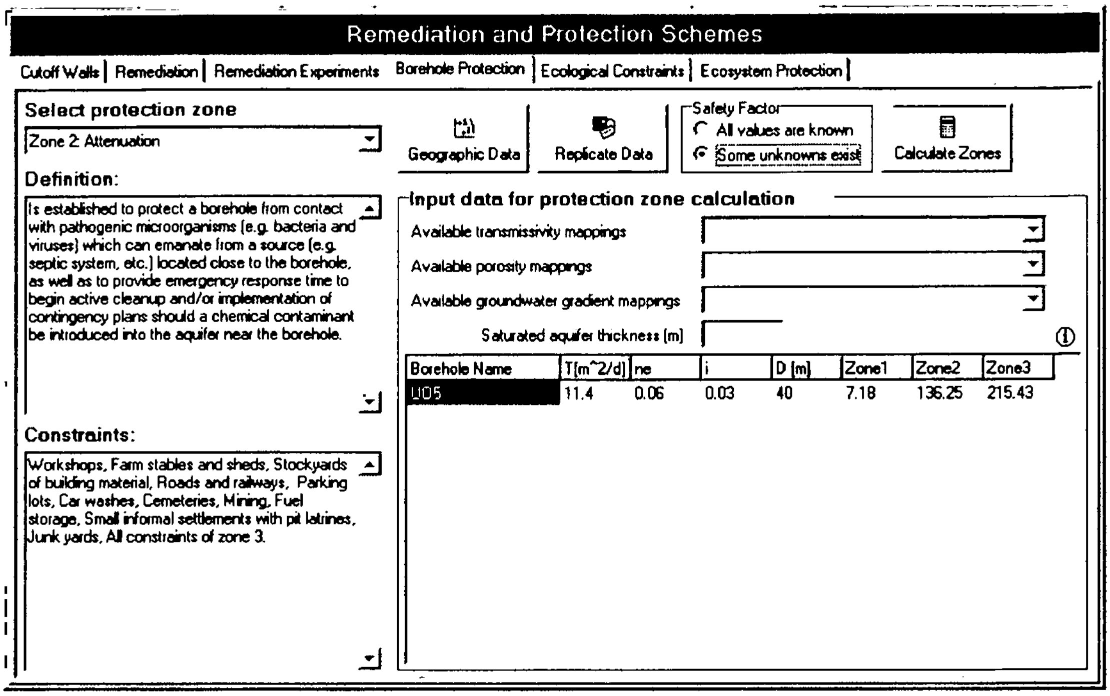


Figure 8-3. Protection zone calculations for borehole UO5 when pumping at 1 L/s

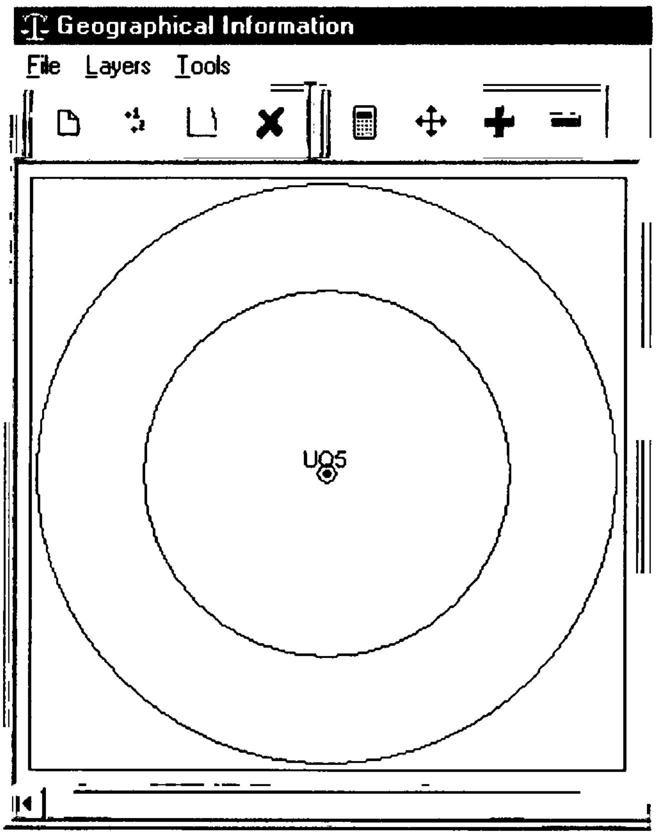


Figure 8-4. Graphical representation of the protection zones for borehole UO5

It must be noted that the protection zones shown in Figure 8-4 are based on a matrix transmissivity and porosity value. However if the transmissivity of the fracture zone is taken as 100 m^2/d, the porosity as 49% and the saturated thickness as 2 m, the following values are obtained for the different zones of protection:

- Zone 1 = 154.29 m
- Zone 2 = 213.22 m
- Zone 3 = 337.13 m

By selecting "Ecosystem Protection" the groundwater gradient towards an aquatic ecosystem and zone of protection can be determined. For example take the values used in the Mutshindudi River Catchment assessments. The results of the protection options are shown in Figures 8-5 and 8-6.

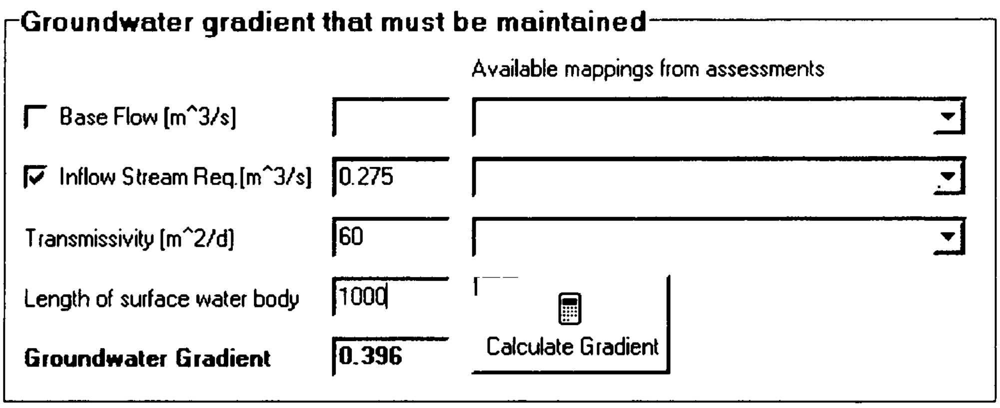


Figure 8-5. Groundwater gradient calculation

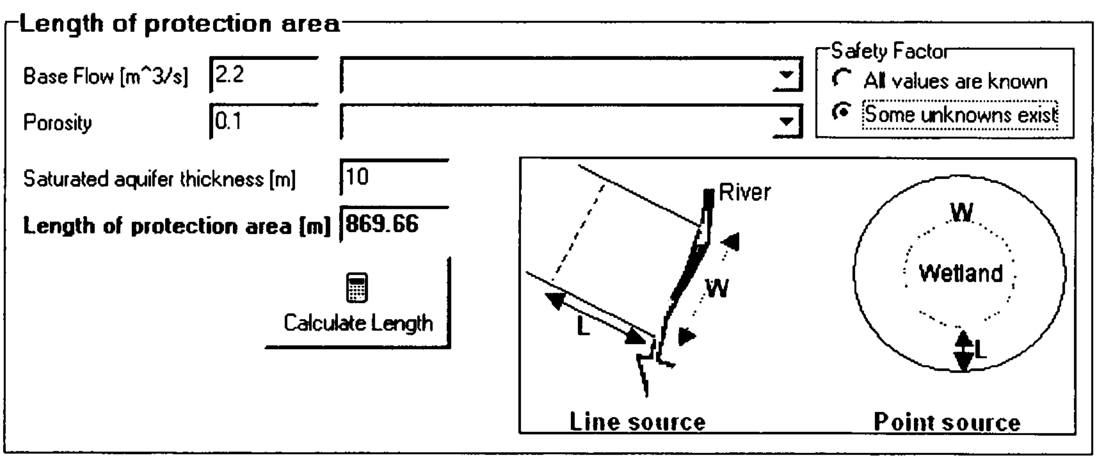


Figure 8-6. Protection zone for aquatic ecosystem

The user must realise that the gradient and protection zone must be applied in conjunction with the constraints, viewed when selecting "Ecological Constraints".

8.3 REMEDIATION

Remediation refers to the cleanup or other methods used to remove or contain a toxic spill or hazardous materials from a contaminated site. Remediation is a complex subject that is site-specific and will therefore not be discussed in detail. The section on remediation will be divided into two. The first section will focus on some experiments conducted concerning remediation. These experiments will give the reader an indication of the possible success of a remediation project. The second section will discuss various remediation options.

8.3.1 Possibilities of remediation

Experiments were conducted to determine the amount of NaCl and Na_2SO_4 that can be retrieved from various sandstones, shales and a quartzite. The various cores were soaked in strong NaCl and Na_2SO_4 solutions. The concentrations of NaCl and Na_2SO_4 used are 3 g/10 ml and 2.5 g/10 ml deionized water respectively. The core was then placed in deionized water and the increase in electrical conductivity was measured with time. The results of can be seen in Figure 8-7.

The results of the experiments are listed in Table 8.4. It is clear that the success of remediation can vary from about 50% to almost 100%. Most of the experiments were performed more than once to ensure the validity of results. The exceptions were sandstone with a porosity of 4.4% and shale with a porosity of 0.83%, due to the fact that limited core available. It is important to note that factors such as continuous flushing with deionized water and natural attenuation can improve the success rate.

Table 8.4: Results of remediation experiments

Formation	Porosity (%)	Amount NaCl retrieved (%)	Amount Na_2SO_4 retrieved (%)
Sandstone (coarse grain)	10.9	-	91
Sandstone (medium grain)	7.1	95	70
Sandstone (medium grain)	6.1	96	75.5
Sandstone (fine grain)	4.4	85	77
Shale	1.12	-	58
Shale	0.92	93.5	63
Shale	0.83	92	49
Quartzite	0.19	96	65

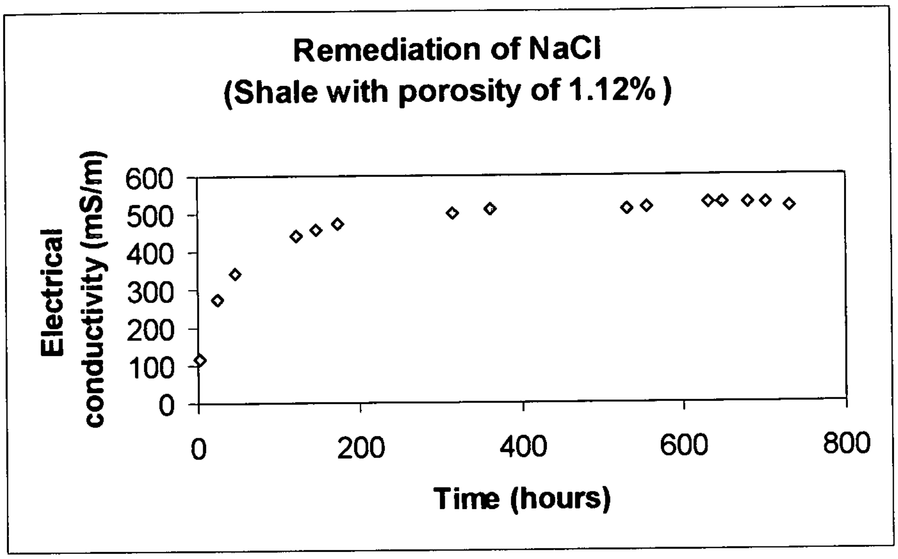


Figure 8-7. Typical remediation graph

The information from remediation experiments will be stored in the DT where the user will be able to browse the information.

8.3.2 Remediation options

Remediation options are site-specific and therefore are not discussed in detail in this thesis. However the DT does contain information on most of the remediation techniques available (refer to Table 8.5). The user will be able to browse this data.

Table 8.5: Remediation options *(Summarised from http://www.clu-in.org/remed1.cfm)*

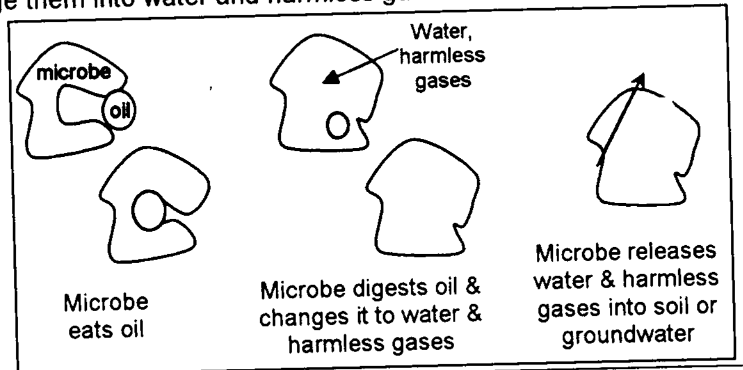
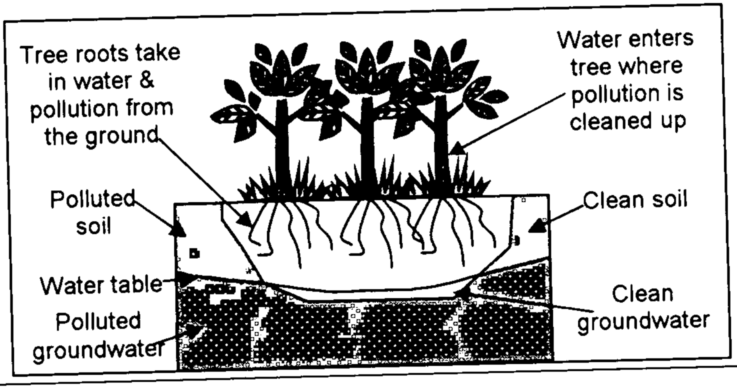
Remediation option	How it works	More information
Bioremediation	Natural clean up of harmful chemicals in groundwater. Microbes present in the soil and groundwater digest certain chemicals (eg petrol and oil) and change them into water and harmless gases.  	• Takes advantage of natural processes. • Do not have to excavate or pump. • Prevents the release of harmful gases into the air. • Does not require much equipment or labor. • The time it takes depends on: o Type and amount of chemicals present. o Size and depth of polluted area. o Type of soil and the conditions present. On average it can take a few months to several years.
Phytoremediation	Uses plants to clean up pollution (metals, pesticides, explosives & oil). Plants also prevent wind, rain and groundwater from carrying pollution away from site. Plants remove harmful chemicals when their roots take in water, therefore they can clean up chemicals as deep as their roots grow.  	Once inside plant chemicals are: • Stored in roots, stems or leaves. • Changed into less harmful chemicals. • Changed into gases that are released when the plant transpires. The method can be harmful to insects, animals and humans eating plants or release harmful gases into the atmosphere. The advantages are: • Does not require much equipment or labor. • Trees and plants make site attractive. • Do not have to excavate or pump. The time it takes depends on: • Type and number of plants zused. • Type and amount of chemicals present. • Size and depth of polluted area. • Type of soil and the conditions present. On average it takes many years to clean up a site.

Table 8.5 continued

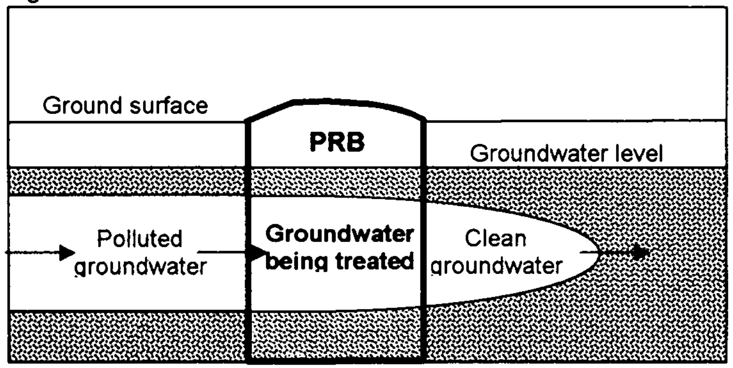
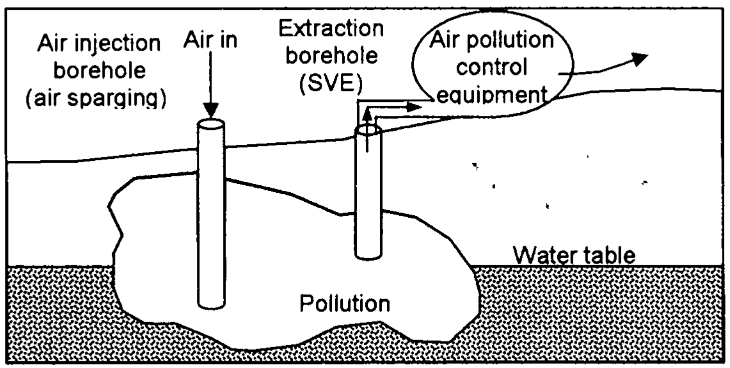
Permeable reactive barriers (PRB)	A PRB is a wall built below the surface to clean up groundwater. The wall allows groundwater to flow through while reactive material in the wall traps and changes harmful chemicals to harmless chemicals. 	Advantages: • No moving parts, no noise. • Polluted water cleaned up underground. • No need to pump. • No equipment above ground so site can be used. Disadvantage: • Some polluted soil must be removed to build barrier. Works best at sites with loose, sandy soil and a steady flow of groundwater. The pollution must not be deeper than 15 m. The time it takes depends on the type and amount of pollution and the rate at which groundwater moves.
Soil vapor extraction (SVE) and air sparging	SVE removes harmful chemicals in the form of vapors from the soil above the water table by means of a vacuum. Air sparging uses air to help remove harmful vapors from polluted soil and groundwater below the water table. Both work best on solvents and fuel. 	Advantages: • Faster than natural processes. • Boreholes and equipment are easy to maintain. • Reaches greater depths than methods involving digging up soil. • Effective in removing any type of pollution that can evaporate. • Helps clean up pollution by encouraging the growth of microbes. Disadvantages: • Must ensure harmful vapors are collected and disposed of properly. • Requires drilling of extraction and air injection boreholes in the polluted area. Works best in loose soils – like sand and gravel. The time it takes depends on the size and depth of polluted area and, the type of soil and the conditions present. The injected air can be heated to speed up the process. Heated soil helps evaporate chemicals faster. Other sources of heat (eg steam or hot water) can be pumped into injection boreholes to heat up the soil.

Table 8.5 continued

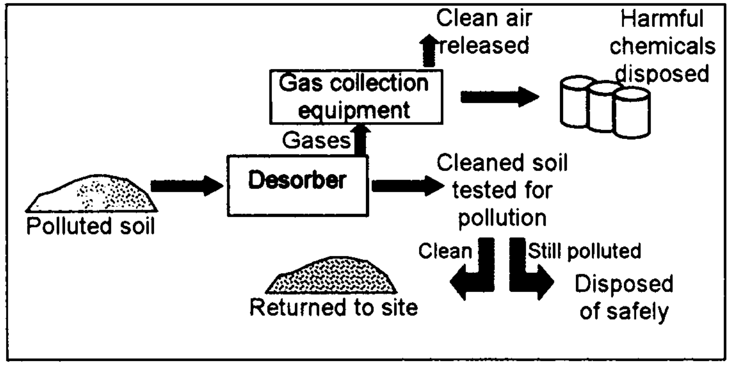
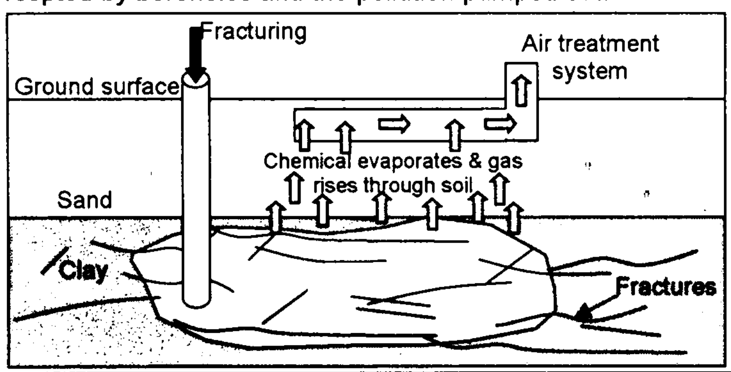
Thermal desorption	This method removes harmful chemicals from soil and other material like slug and sediment by using heat to change chemicals into gases. These gases are collected by special equipment. The clean soil is returned to the site.  	Thermal desorption works well at sites with dry soil and certain types of pollution such as fuel oil, coal tar, chemicals that preserve wood and solvents. Advantages: • Faster clean up method than most. • Equipment often costs less to build and operate than equipment for other clean up methods using heat. Disadvantage: • Soil must be transported off-site, which costs money. The time it takes depends on the amount of polluted soil, the condition of the soil and, the type and amount of harmful chemicals present. A system can clean over 20 tons of polluted soil per hour.
Fracturing	Fracturing is used to crack rock or dense soil. It is not necessarily a cleanup method itself, it rather aids other cleanup methods to be more effective. Fractures create paths through which pollutants can travel. These pollutants can then be evaporated out of the soil or the fractures can be intercepted by boreholes and the pollution pumped out.  	Do not conduct near underground pipelines or above-ground structures. Fracturing offers a way of reaching pollution deep in the ground where it would be difficult or costly to dig down so far. Fracturing can reduce the number of boreholes needed for certain cleanup methods, which can save time and reduce cleanup costs. Often fracturing is used to help clean up non-aqueous phase liquids (NAPLs) – chemicals that don't dissolve readily in groundwater. The time it takes depends on the size and depth of the polluted area, the types and amounts of harmful chemicals present, the type of soil or rock and the cleanup method used. Fracturing rock and soil does not take very long – it may only take a few days. However, the actual cleanup may take months or years.

Table 8.5 continued

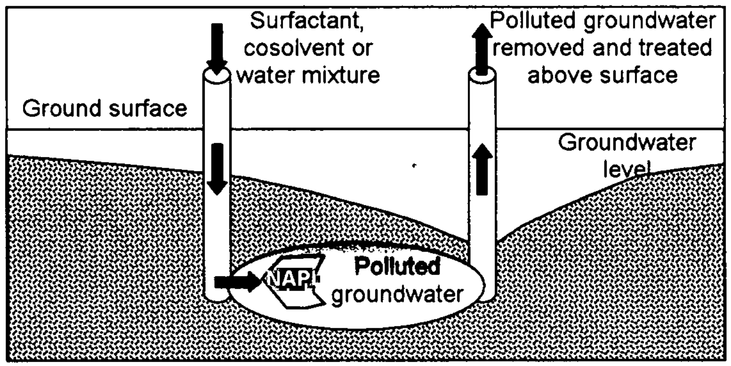
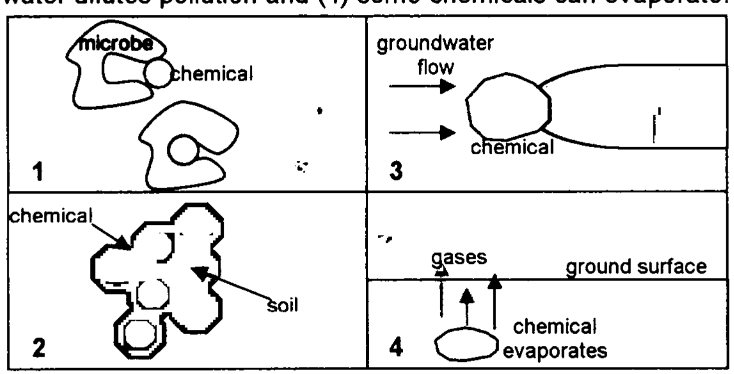
In situ flushing (steam, water or chemicals)	In situ flushing is a way to clean up harmful chemicals in polluted soil and groundwater by pumping water or chemicals (normally surfactants or cosolvents) into the ground. This helps flush the harmful chemicals from the ground by moving them towards boreholes that pump the chemicals out. Therefore in situ flushing is used to help pump and treat groundwater. 	This method is often used in NAPL remediation. It works best in soil that is very permeable and the soil/rock underneath the polluted area is not very permeable. Advantage: • Avoids the expense of digging up soil for disposal or clean up. Disadvantages: • Workers that handle chemicals pumped down the boreholes must wear protective clothing. • Also surfactant or cosolvent left behind after clean up can be harmful. • Can be expensive and difficult to implement. The target contaminant group for soil flushing is inorganics, including radioactive contaminants. The time it takes depends on the size and depth of the polluted area, the type and amount of NAPL, the type of soil and conditions present and how groundwater flows through the soil/rock matrix. Clean up of a site can take months or years.
Monitored natural attenuation	Relies on natural processes to clean up groundwater or soil. There are four methods: (1) microbes digest chemicals, (2) chemicals sorb to the soil/rock matrix. This does not clean up pollution but keeps it from spreading, (3) groundwater dilutes pollution and (4) some chemicals can evaporate. 	Regular monitoring is needed to make sure pollution does not leave site. Advantages: • No digging or construction and nothing has to be added to clean up pollution. • Less disruptive to neighborhood and environment. • Cleanup workers not in contact with pollution. • Less equipment and labor. Disadvantage: • Monitoring may be costly. The time it takes depends on the size and depth of the polluted area, the type and amounts of chemicals present and the type of soil and conditions present. Clean up usually takes years to decades. These methods are used when other methods do not work.

Table 8.5 continued

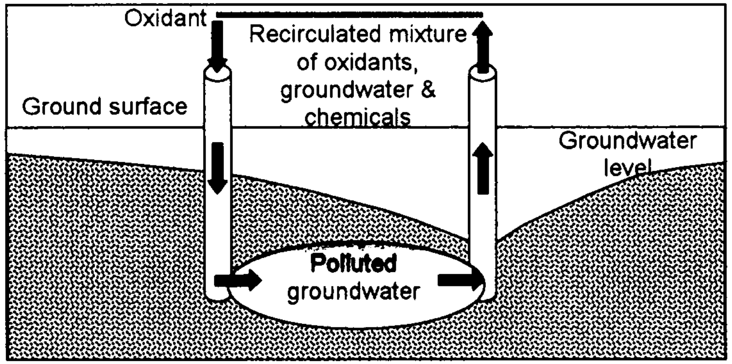
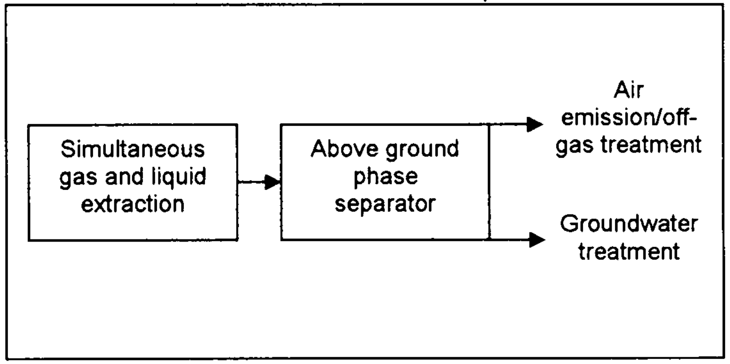
Chemical oxidation - same methodology as bioventing	This process uses chemicals called oxidants to destroy pollution in soil and groundwater. Oxidants change harmful chemicals into harmless ones like water and carbon dioxide. Chemical oxidation can destroy many types of chemicals like fuels, solvents and pesticides.  	Chemical oxidation can create enough heat to boil water. The heat can cause the chemicals underground to evaporate. Advantages: • Do not have to dig or excavate. • No boreholes are needed. • Saves time and money. • Can reach pollution deep within groundwater system. Disadvantages: • Oxidants are corrosive. • People who work with oxidants must wear special clothing. • Some oxidants can explode. The time it takes depends on the size and depth of the polluted area, how groundwater flows and the type of soil and conditions present. In general chemical oxidation is faster than most methods. Clean up times can be measured in months, rather than years.
Fluid/Vapor Extraction (Two phase extraction)	A vacuum system simultaneously removes liquid and gas from low permeability or heterogeneous formations. It removes contaminants from above and below the water table. The system lowers the water table around the borehole, exposing more of the formation. Contaminants in the newly exposed vadose zone are then accessible to vapor extraction.  	Advantages: • Can remove contaminants more efficiently than pump-and-treat. • Because of the turbulence created during extraction, most of the contaminants in the water are stripped away, and little additional treatment is needed. Disadvantage: • Fluid/vapor extraction requires both water treatment and vapor treatment. The target contaminant groups for fluid/vapor extraction are VOCs and fuels. It is more effective than SVE for heterogeneous clays and fine sands. Fluid/vapor extraction can be combined with bioremediation, air sparging, or bioventing when the target contaminants include long-chained hydrocarbons.

Table 8.5 continued

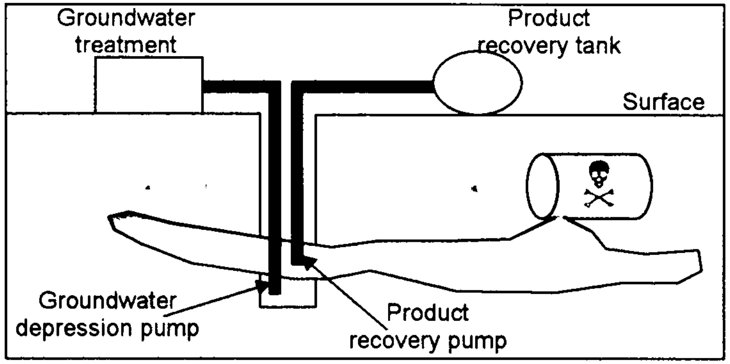
Dual phase extraction	Dual-phase extraction (DPE), also known as multi-phase extraction or vacuum-enhanced extraction, is a technology that uses a high vacuum system to remove various combinations of contaminated groundwater, separate-phase petroleum product, and hydrocarbon vapor from the subsurface.  	The DPE process for undissolved liquid-phase organics, also known as free product recovery, is used primarily in cases where a fuel hydrocarbon lens more than 20 cm thick is floating on the water table. The target contaminant groups for dual phase extraction are VOCs and fuels (eg LNAPLs). Dual phase vacuum extraction is more effective than SVE for heterogeneous clays and fine sands. However, it is not recommended for lower permeability formations due to the potential to leave isolated lenses of undissolved product in the formation.
Bioslurping	Bioslurping combines the two remedial approaches of bioventing and vacuum-enhanced free-product recovery. Bioventing stimulates the aerobic bioremediation of hydrocarbon-contaminated soils. Vacuum-enhanced free-product recovery extracts LNAPLs from the capillary fringe and the water table.	It is a cost-effective in situ remedial technology. Bioslurping is applicable at sites with a deep ground water table (> 9 m). Disadvantages: • Less effective in low-permeability soils. • Low temperatures slow remediation. • The off-gas requires treatment before discharge. • At some sites, bioslurper systems can extract large volumes of water that may need to be treated. • Since the fuel, water and air are removed, these mixtures may require special oil/water separators or treatment before the process water can be discharged. Operation and maintenance duration for bioslurping varies from a few months to years, depending on site specific conditions.

Table 8.5 continued

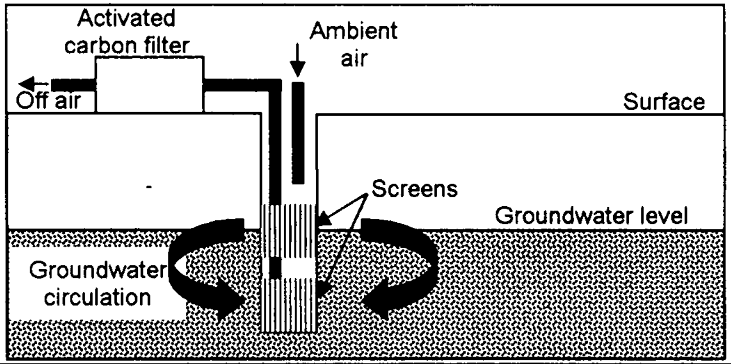
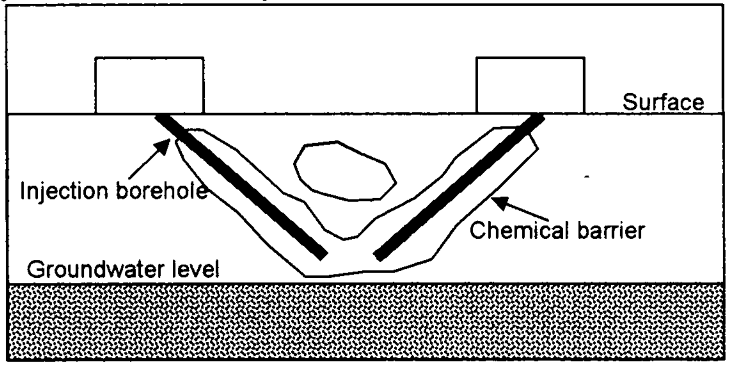
In-well air stripping	Air is injected into a double-screened borehole, lifting the water in the borehole and forcing it out the upper screen. Simultaneously, additional water is drawn in the lower screen. Once in the borehole, some of the VOCs in the contaminated groundwater are transferred from the dissolved phase to the vapor phase by air bubbles. The contaminated air rises in the borehole to the water surface where vapors are drawn off and treated by a soil vapor extraction system.  	The target contaminant groups for vacuum vapor extraction are halogenated VOCs, SVOCs, and fuels. Variations of the technology may allow for its effectiveness against some nonhalogenated VOCs, SVOCs, pesticides, and inorganics. Typically, in-well air stripping systems are cost-effective. Disadvantages: • Fouling may occur by infiltrating precipitation containing oxidized constituents. • Shallow aquifers limit effectiveness. • Limited to sites with K > 10^{-2} m/d and should not be utilised at sites that have lenses of low-K deposits. • In well air stripping may not be effective at sites with strong natural flow patterns.
Chemical barriers	Chemically based barrier materials involve the use of agents either to reduce permeability of the aquifer or to cause a chemical reaction to detoxify or reduce the mobility of the contaminant.  	Contaminants such as uranium, molybdenum, chromium, arsenic, copper, lead, zinc, and radium can potentially be removed from groundwater. Advantages: • Avoids the water management and groundwater flow interruption problems. • If the permeable barriers are designed to destroy the contaminants rather than absorb them, further management or removal of the hazardous substances becomes unnecessary.

Table 8.5 continued

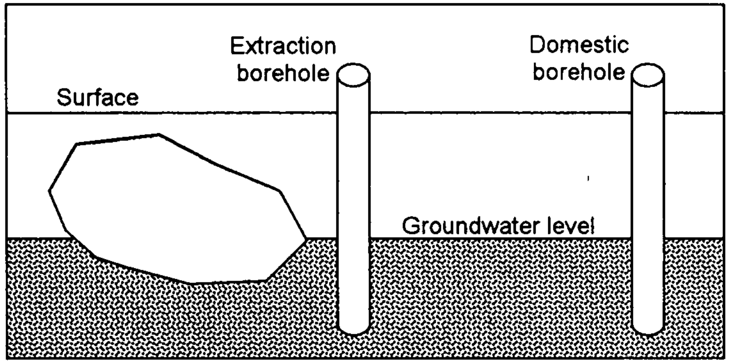
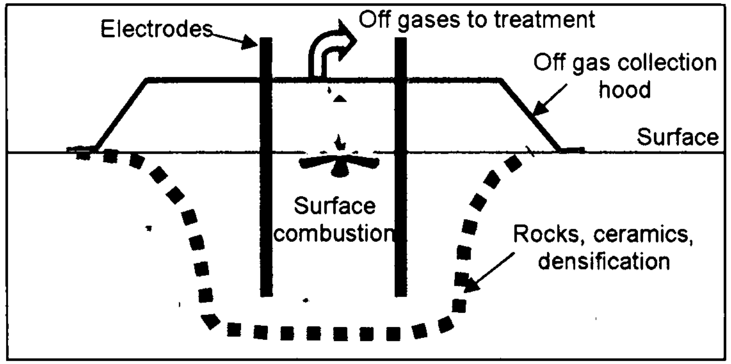
Dams, ditches and drains	Dams are used to control surface water flow that carries either dissolved or suspended contaminants. Ditches are used to control the flow of surface water containing dissolved or suspended contaminants. Less commonly, ditches are used to control groundwater flow. Drains are used to capture groundwater or surface water for the purposes of treatment or containment. Dams, ditches and drains are not a treatment and do not target any specific group of contaminants.	Advantage: • The techniques to construct are well understood. Disadvantages: • The limitations are that in certain soil conditions underflow beneath the dam may occur, and the structure may require constant maintenance. • A limitation of ditches is that in high permeability soils, the water will simply drain into the soil. • The effectiveness of a drain is problematic in complex geohydrological systems.
Pumping systems	Extraction boreholes are used to control groundwater flow. The purpose is to contain plume migration by redirecting groundwater from source areas or to control groundwater plumes by creating preferential flow patterns.  	Target contaminant groups are mobile and soluble organics and inorganics. Extraction borehole systems are relatively simple to implement and use standard equipment readily available from multiple sources.
Radioactive decay	Radioactive decay is a natural process where radioactive elements spontaneously emit energetic particles such as electrons or alpha particles. These emissions are harmful. The level of these emissions drops over time as the element reaches a stable state. Incorporating radioactive decay into the remediation strategy also includes monitoring and some form of control.	Radioactive decay is the only method to eliminate the risk of radioactive elements as no treatment exists to eliminate the property of radioactivity.

Table 8.5 continued

In Situ Vitrification	The in situ vitrification (ISV) process can destroy or remove organics and immobilise most inorganics. ISV uses an electric current to melt soil or other earthen materials at extremely high temperatures (1600 to 2000°C) and thereby immobilises most inorganics and destroys organic pollutants by pyrolysis. Process depths up to 6 m have been achieved in relatively homogeneous soils. 	The process can be used on a range of VOCs, SVOCs, and other organics, including dioxins and polychlorinated biphenyls (PCBs), and on most priority pollutant metals and radionuclides. The vitrification product is a chemically stable and leach resistant. The process destroys and/or removes organic materials. Radionuclides and heavy metals are retained within the molten soil. Factors that may limit the applicability and effectiveness of the process include the following: • Subsurface migration of contaminants into clean areas because of soil heating. • Combustible organics.
Conventional excavation	Contaminated material is removed and transported to permitted off-site treatment and/or disposal facilities. Excavation and off-site disposal is a well proven and readily implementable technology.	Disadvantages: • Generation of emissions may be a problem during operations. • Distance from site to the nearest disposal facility will affect cost. • Transportation of the soil through populated areas may affect community acceptability. • Disposal options may be limited.
Pump and treat	Conventional pumping is used for cleanup of organics and inorganics (metals, anions, and radionuclides) in groundwater. The system, consisting of appropriate access boreholes for groundwater extraction, removes contaminants that are dissolved in the water for treatment at the surface. This technology is simple to design and operate, uses standard equipment available from many sources, and treats all types of dissolved contamination.	Advantage: • It can be implemented quickly and is compatible with adjunct technologies. Disadvantages: • Not applicable to fractured rock or clay. • A poor choice for contaminants that adsorb or those with low solubilities.

8.3.3 Example

When selecting the remediation and protection screen appears (Figure 8-2). Tables 8.1, 8.4 and 8.5 are documented under "Cutoff walls", "Remediation" and "Remediation Experiments". The user can scroll through these tables. For example if the user wants more information concerning bioremediation, the topic has to be selected from the menu in the top left-hand corner of the screen and all the information conceming bioremediation will appear (Figure 8-8).

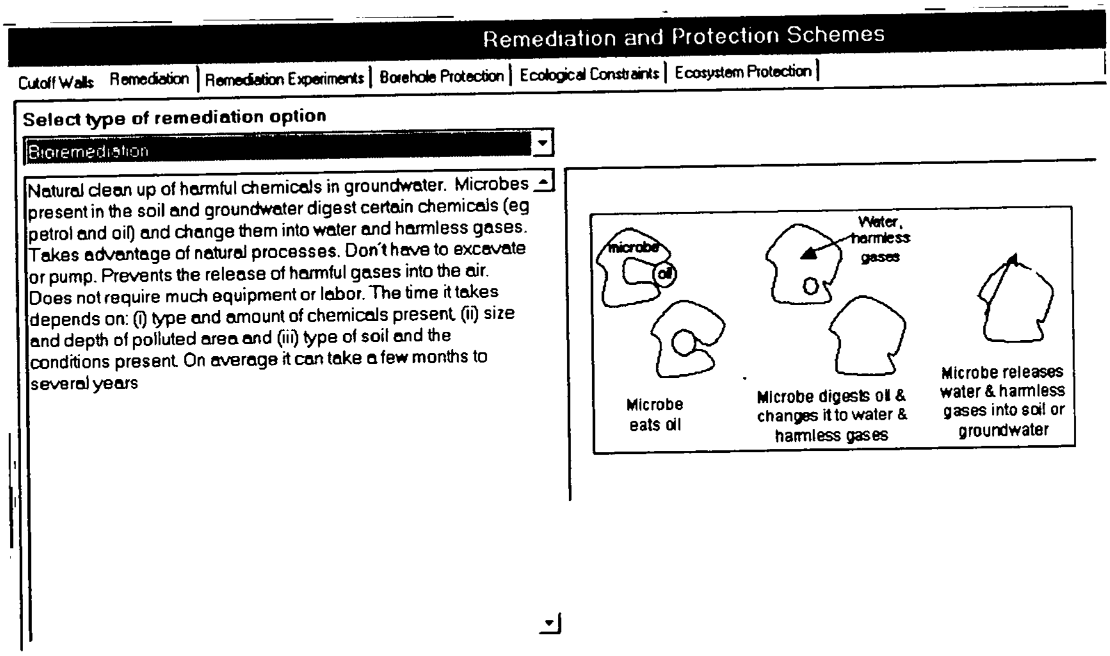


Figure 8-8. Results of enquiry concerning bioremediation

Chapter 9

Cost-benefit-risk Analysis

9.1 BACKGROUND

Cost-benefit-risk analysis is widely used as a tool in project appraisal to optimise project design, to assess policies and regulations, and to evaluate decisions entailing more or less measurable economic consequences (Abelson, 1979). Cost-benefit-risk analysis is defined as a set of procedures used for defining, comparing and measuring benefits and costs, which originate from either an investment or an operation. Cost-benefit-risk analysis is flexible and adaptable. However, the assessor should keep the suitability of a cost-benefit-risk analysis for different types of projects in mind before an attempt is made to perform the analysis.

Cost-benefit-risk analysis shapes the framework for decision-making. The fundamental rule for cost-benefit-risk analysis is that decisions are made by decision-makers, and therefore it is an aid for decision-making and not the decision itself.

The advantages of a cost-benefit-risk analysis include transparency, the provision of a framework for consistent data collection and identification of gaps and uncertainty in knowledge. Cost-benefit-risk analysis does not take the "rights" of future generations into account and where environmental protection is desirable, the reasons for the protection are often not quantifiable, for example in the case of social values.

9.2 METHODOLOGY

9.2.1 General

The framework discussed in this section is an early stage monetary risk based cost-benefit-risk analysis, considering both the probability and economical consequences of depleting and contaminating groundwater resources. The framework is aimed at providing a basis for cost-effective decision-making regarding groundwater protection and management actions. A major objective in cost-effective groundwater protection and management should be that of systematically obtaining optimal value from existing geohydrological and other information *before* performing detailed studies (Rosen and LeGrand, 1997). In cost-efficient groundwater protection and management work the costs for protective actions must be in balance with the economical risks of contamination.

9.2.2 Monetary Risk Analysis *(Summarised from Freeze et al., 1990; Janse Van Rensburg, 1992)*

In a decision problem, the benefits, costs and risks of each alternative are taken into account by defining an objective function, ϕ_i, for each alternative i = 1, . . . , n. The objective function should reflect the specific problem and the preferences of the decision-maker, and thus, varies according to the key variables involved (Rosen *et al.*, 1998). The objective function has the general form:

$$\phi_i = \sum_{t=0}^{T} \frac{1}{(1+r)^t}\left[B_i(t) - C_i(t) + V_i(t) - R_i(t)\right] \tag{9.1}$$

where

$B_i(t)$ = Benefits of alternative i in year t

$C_i(t)$ = Costs of alternative i in year t

$V_i(t)$ = Remediation of alternative i in year t

$R_i(t)$ = Risks of alternative i in year t

r = Discount rate

T = Time horizon

The time horizon is relatively short, in the order of 20 – 50 years. The discount rate is the market interest rate on borrowed money.

The objective function presents the net present value of alternative i. The objective of the design must be met to maximise profit or minimise loss.

Remediation can be defined as:

$$V(t) = P_S(t) B_S(t) \gamma(B_S)$$

where

$P_S(t)$ = Probability of success in year t

$B_S(t)$ = Benefits associated with success in year t

$\gamma(B_S)$ = Normalised unity function

The benefits $B_S(t)$ associated with success in a remedial clean up could include permission to reopen operation, removal of legal liabilities and the return of goodwill to the community.

The risk R(t) is defined as the expected costs associated with the probability of failure:

$$R(t) = P_f(t)C_f(t)\gamma(C_f)$$

where

$P_f(t)$ = Probability of failure in year t

$C_f(t)$ = Costs associated with failure in year t

$\gamma(C_f)$ = Normalised unity function

The term C(t) typically represents all fixed and operational costs for each alternative. The $C_f(t)$ term includes the costs that would arise due to the depletion and/or contamination of a groundwater resource. They would include any fines, taxes or charges that might be levied by government for failing to comply with legislation, the costs of litigation, the costs of remedial action; and the value of any revenues foregone should the operation be stopped or curtailed. Goodwill for the community is also included here. When avoiding risks γ is usually greater than one, however for a neutral approach γ is equal to one.

It is important to note that either the failure term OR the success term must be used in Equation 9.1.

9.2.3 Cost-benefit-risk analysis in the decision tool

The decision tool does not calculate risks on a yearly basis, therefore the monetary risk analysis discussed in Section 9.2.2 was simplified and to be included in the decision tool. As there are no calculations concerning the risks involved with the success of remediation in the DT, the option for the success of remediation has not been included.

Time dependency was removed from the calculations, however it is still indirectly taken into account when calculating the benefits and costs. The decision tool takes a neutral approach and assumes:

$$\gamma(C_f) = 1.$$

The final methodology used in the decision tool is summarised in Figure 9-1.

Cost-benefit-risk Analysis

PROBABILITY OF FAILURE
Groundwater depleted or contaminated

⬇

Calculation

$$\phi_i = \frac{1}{(1+r)}[B_i - C_i - R_i]$$

where r = discount rate, B_i = all benefits associated with alternative i, C_i = all fixed and operational costs associated with alternative i and R_i = P_fC_f with P_f = probability of failure and C_f = costs associated with failure.

⬇

Examples of benefits (B): Economical, financial, social, environmental and legal.

Examples of costs (C): Capital and operational.

Examples of costs (C_f): Penalties/fines, costs of drilling new boreholes, protecting groundwater against contamination, legal, loss of reputation and social.

Probability of failure (P_f): Risk determined in Chapters 4, 5, 6 & 7.

Failure occurs when boreholes dry up AND/OR target water quality ranges for aquatic ecosystems and/or maximum drinking water guidelines are exceeded (Refer to Appendix B, Section B2).

Figure 9-1. Methodology for Cost-benefit-risk analysis

9.3 EXAMPLE

When selecting "$" in the DT software the cost-benefit-risk analysis screen appears (Figure 9-2). The user can then decide what to include in the cost-benefit-risk analysis: the user can consider sustainability options, contamination options, health options, ecological options or any combination of the four. For each option (Figure 9-2) the user must enter the discount rate (interest %), all the costs involved and the probability of failure, which is obtained from performing a sustainable, contamination,

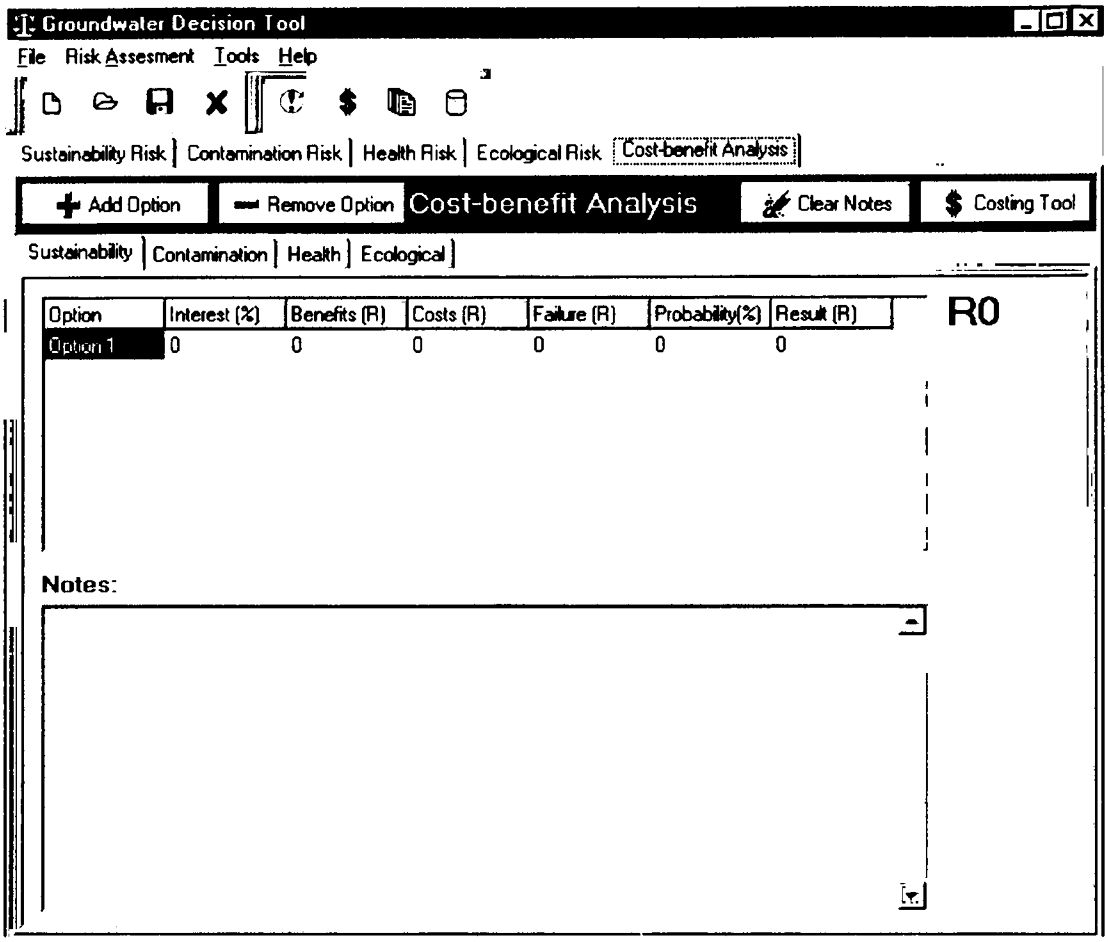


Figure 9-2. Initial screen for cost-benefit-risk analysis

health or ecological risk assessment. The DT will then calculate the final costs associated with the option. However by selecting "Costing Tool" the DT provides the user with a breakdown of what must be included in the costs. The DT will then calculate the final costs. In addition the user can enter which risk assessment results must be used, and the DT will automatically include the respective risk in the calculation. The "Notes" that occurs below the costing table allows the user to record information concerning each option. The DT does not optimise the objective function and the user must decide on the option best suited for the situation under investigation.

For example consider the hypothetical case study adapted from the one discussed by Rosen and LeGrand (1997) where a small storage facility for an organic compound is situated 200 m up-gradient from the property boundary (Figure 9-2). The facility contains one storage tank above ground containing 100 m^3 of the organic compound. Leaks have been found in similar tanks and the organic compound is highly soluble. The owner of the adjacent property is likely to take legal action if contamination occurs.

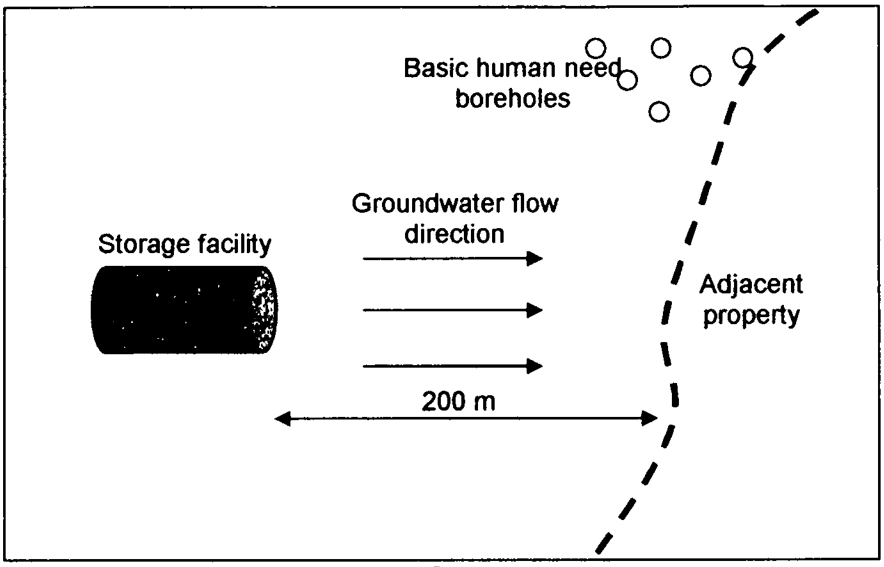


Figure 9-3. Sketch of area

Various contamination risk assessments were generated and the values used in the cost-benefit-risk analysis tool to determine the financial implications of each risk. The contamination risk assessment considered the possibilities of pollution entering the adjacent property. In addition there are approximately 6 basic human need boreholes in the area. Therefore a health risk assessment will have to be conducted for various scenarios to determine the health impacts at the basic human need boreholes.

As the health risk assessment and contamination assessment have been discussed in detail they will not be included here, hypothetical risks will be assumed for each scenario. The scenarios, included in the cost-benefit-risk analysis, are summarised in Table 9.1.

Table 9.1: Summary of scenarios used in cost-benefit-risk analysis

Scenario	**Description**	**Associated risks (%)**	
		Health	**Contamination**
1	There is a leak in the tank and the owner does not take any preventative measures. The owner also refuses to remediate the plume.	70	99
2	The owner builds a cutoff wall along the boundary of the property.	99	10
3	There is a leak in the tank and the owner does not take any preventative measures. However he is prepared to pay for the remediation.	70	99

The risks and associated costs of each of these scenarios are included in the cost-benefit-risk analysis. The contamination cost-benefit-risk values for scenario 1 are shown in Figures 9-4 and 9-5.

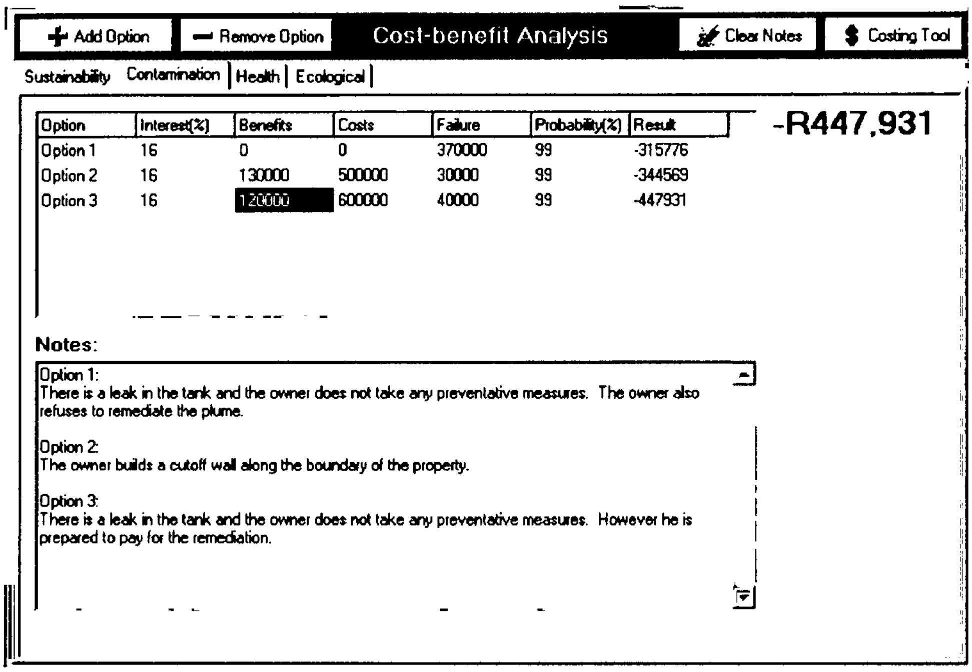


Figure 9-4. Contamination cost-benefit-risk analysis for scenario 1

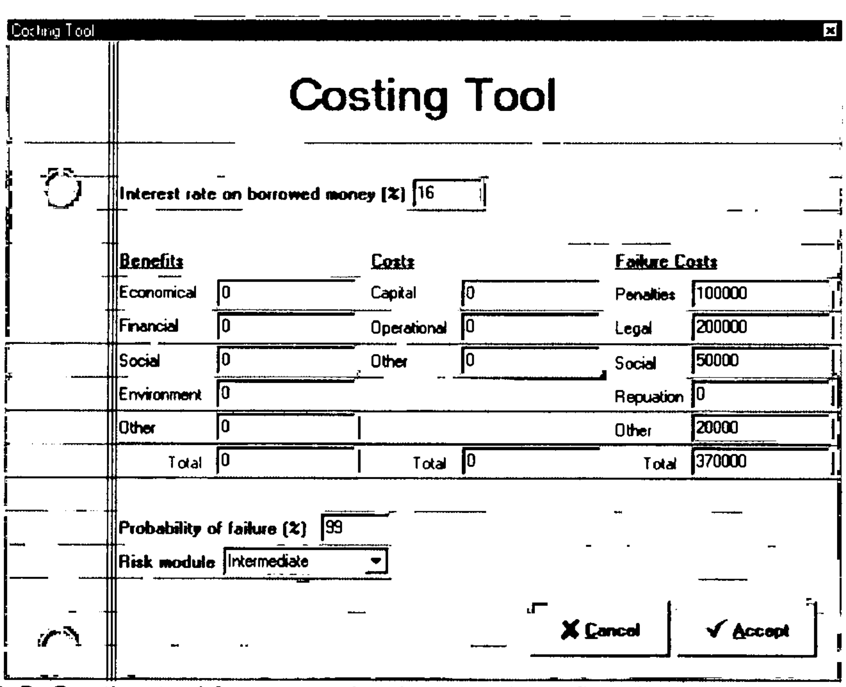


Figure 9-5. Costing tool for contamination cost-benefit-risk analysis for scenario 1

The DT tool can also generate a report. No reports have been generated in any of the examples discussed in this thesis, however a report can be generated for all of them. To demonstrate the generation of a report, the results from the above scenario will be shown in report format.

When selecting  the report generator will appear. The initial screen of the report generator can be seen in Figure 9-6. The user can given the report a title and select the information he wishes to include in the report.

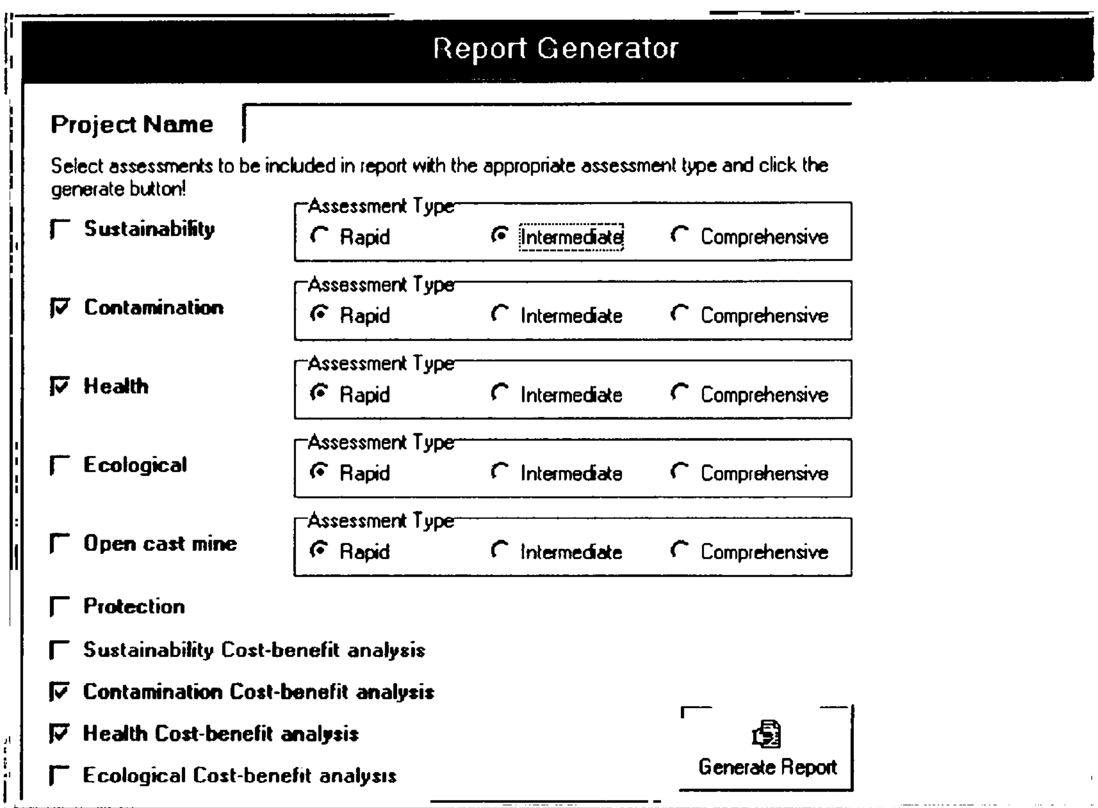


Figure 9-6. Initial screen of report generator

In this example the results of the contamination and health cost-benefit-risk analysis have been selected. The relevant sections of the report are shown below.

Health Cost-benefit Analysis

Option 1:
There is a leak in the tank and the owner does not take any preventative measures. The owner also refuses to remediate the plume.

Option 2:
The owner builds a cutoff wall along the boundary of the property.

Option 3:
There is a leak in the tank and the owner does not take any preventative measures. However he is prepared to pay for the remediation.

Option , Cost (R)

Option 1 , -138793

Option 2 , -196293

Option 3 , -521552

Contamination Cost-benefit Analysis

Option 1:
There is a leak in the tank and the owner does not take any preventative measures. The owner also refuses to remediate the plume.

Option 2:
The owner builds a cutoff wall along the boundary of the property.

Option 3:
There is a leak in the tank and the owner does not take any preventative measures. However he is prepared to pay for the remediation.

Option , Cost (R)

Option 1 , -315776

Option 2 , -344569

Option 3 , -447931

Chapter 10

Discussion, Conclusions and Recommendations

10.1 GENERAL

Water supply of acceptable quality is necessary for the improvement of the quality of life, and is essential in the maintenance of all forms of life. Limited water resources in South Africa have led to more emphasis being placed on groundwater. This thesis introduces a risk-based decision tool to be used for the management of groundwater.

A risk can be defined as the probability that an adverse event will occur under specified circumstances. Effective decision-making involves the management of risks: identifying, evaluating, selecting and implementing actions to reduce risk. Risk assessment is a technique that provides such information to the manager, thereby facilitating the complex and integrated decisions necessary.

In order to obtain accurate results from the risk assessment process, accurate data must be used. This thesis sets aside a chapter to discuss both aquifer and contaminant parameters and methods to obtain both sets of parameters.

The DT is divided into three tiers namely a rapid, intermediate and comprehensive assessment. For each of the tiers the following risk assessments can be performed:

- A groundwater risk assessment can be defined as the probability of an adverse effect or effects on the sustainability and/or quality of groundwater associated with measured or predicted hazards.
- A groundwater health risk assessment can be defined as a qualitative or quantitative process to characterise the probability of adverse health effects associated with measured or predicted levels of hazardous agents in groundwater.
- Ecological risks of interest differ qualitatively between different stresses, ecosystem types and locations. A groundwater ecological risk assessment quantifies the impacts of groundwater quantity and quality on ecosystems.

Once the desired risk assessments have been completed, cost-benefit-risk analyses can be used to aid in decision-making regarding the management of a groundwater resource. A cost-benefit-risk analysis is defined as a set of procedures used for defining, comparing and measuring benefits and costs, which originate from either an investment or the operation of an activity.

Since the early 1980's geohydrologists and engineers have developed a number of techniques for protecting groundwater. Protection is divided into two categories: measures to prevent failure and pollution of water resources, and measures to remedy the effects of polluted water resources.

On completion of the different aspects of the DT a report will be generated including the input data and the results of the risk assessments and cost-benefit-risk analysis. Depending on the user, prevention measures can be included. Unfortunately no in-depth study has been completed on remediation options, but the user will be able to browse through the various options.

The information acquired from the DT can be used for risk management.

10.2 INTERPRETATION OF RISK

Risk assessment is a way of thinking about or analysing a situation, and as such it is a combination of science and judgement. Risk is a combination of two factors: (1) the chance that an adverse event will occur and (2) the consequences of that event. Risk values are often stated as a number. This thesis made use of the following ways of expressing a risk:

- When the risk concern is cancer, the risk number represents a probability of the occurrence of cancer cases. For example such an estimate for contaminant x might be expressed as 10^{-6} or 0.000001 – meaning one case of cancer per population of 1 000 000 is expected when the population is exposed to a certain concentration of contaminant x.
- Non-cancer toxic risks compare the average daily dose of a contaminant y to a reference dose calculated for that specific contaminant. The closer the average daily dose comes to the reference dose, the higher the risk. Once the average daily dose is equal to or greater than the reference dose, the risk of a person suffering toxic effects due to exposure to contaminant y is 99%.

- Microbiological risk refers to the probability of infection. As the probability tends to 1, the risk increases to 99%. For example, consider a groundwater resource, there is a 0.9 probability or a 90% chance of a person becoming infected when drinking from the resource. However there is a 10% chance that nothing will happen to the person. Only once the person has drank from the resource, will the person definitely know if he/she has been infected.
- Risks based on fuzzy sets and decision rules have been used throughout the thesis. These risks are based on both professional judgement and, scientific data and calculations. To demonstrate interpreting this method of risk determination, once again consider a groundwater resource with a membership value of 0.9, indicating that the groundwater is mostly drinkable. The risk is then interpreted as the groundwater resource is 10% undrinkable. Only by collecting more accurate data can the membership value change.

It must however be noted that the choice of membership values and decision rules must be chosen with care and tested thoroughly. If this is not done, the fuzzy logic methodology can be inaccurate and produce inconclusive results.

10.3 RECOMMENDATIONS AND CONCLUSIONS

The DT presents a fuzzy logic based method to do risk assessments concerning groundwater. Included are methodologies to characterise fractured rock aquifers. There is ongoing research concerning these aquifers and as new methodologies are developed it is important to include them in the DT.

This DT has been developed over a period of two and half years and even though it has been tested and calibrated by experts, it is important to note that in order to obtain more accurate results, it must be validated over a period of many years.

In addition the database of the DT has been populated with information; it can be expanded and more detail can be added.

The ecological risk assessment is limited to a few indicators to determine the risks for aquatic ecosystems. This assessment can be developed to include aspects such as flow conditions in rivers and fish species. In addition the impacts of groundwater on terrestrial ecosystems need to be considered and included in the ecological risk assessment. Accommodating these factors complicates ecological risk assessments.

The cost-benefit-risk analysis is crude and this can be developed into more comprehensive computations such as those discussed by Jansen van Rensburg (1992).

Even though uncertainty has indirectly been included in the DT. Further development of the DT should include a comprehensive uncertainty analysis. The uncertainty analysis should include aspects such as the quality of data, the relationships between potential hazards and effects of concern and, the methods used to calculate risks. The uncertainty analysis thereby highlights the limitations of the risk assessment allowing decisions to be made in a more transparent fashion.

The DT developed in this thesis relies heavily on the expertise of geohydrologists, assumptions and approximations of real world conditions. Together with the heterogeneities present in groundwater systems it is impossible to guarantee the accuracy of the methodologies and the reader must take this into consideration. However as Hurst (1957) stated: *It is usually better to do something which is 95% effective immediately, rather than to wait several years to improve the solution by 4%.*

The DT can be a useful tool for a groundwater manager to use in order to obtain an understanding of the groundwater situation in a particular area and the impacts thereof. In addition the DT can be used to rank groundwater related problems, thereby making groundwater management and protection an achievable task.

Chapter 11

References

Abelson, P (1979). Cost Benefit Analysis and Environmental Problems. Saxon House, Teakfield Limited, England, p 1-74.

Abramowitz, M and Stegun, IA (1972). Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables. Dover Publications Inc, New York.

Aller, L, Bennet, T, Lehr, JH, Petty, RJ, Hacket, G (1987). DRASTIC: A standardized system for evaluating groundwater pollution using hydrological settings. Prepared by the National Water Well Association for the US EPA Office of Research and Development, Ada, USA.

Appelo, CAJ (2000). Comment on 'Sulfate transport in a Coastal Plain confining unit, New Jersey, USA' (Prucci 1999). Hydrogeology Journal, vol 8, p 455 – 456.

Bangoy, LM, and Drogue, C (1993). Analysis of intermittent pumping tests in fissured fractal aquifers: theory and applications. Journal of Hydrology, vol 158, p 47 –59.

Barcelona, M, Keely, JF, Pettyjohn, WA and Wehrmann, A (1988). Handbook of Groundwater Quality Protection. Science Information Resource Centre, Hemisphere Publishing Corporation, Washington DC, USA.

Barker, JA (1988). A Generalized Radial Flow Model for Hydraulic Tests in Fractured Rock. Water Resources Research, vol 24, p 1796 – 1804.

Boulding, JR (1995). Practical Handbook of Soil, Vadose zone and Ground-Water Contamination: Assessment, prevention and remediation. Lewis Publishers, United States of America.

Braune, E (2000). Groundwater Management in terms of the National Water Act, 1998. In proceedings: course on Ground Water and the National Water and Water Services Acts, University of Pretoria Conference Centre, Pretoria.

Canadian Material Safety Data Sheets (2001). Available on internet at: http://webferret.search.com/click?wf,Campylobacter,,www.hc-sc.gc.ca%2Fhpb%2Flcdc%2Fbiosafty%2Fmsds%2Findex.html,,icq

Cinco-Ley, H & Samaniego, V (1981a). Transient Pressure Analysis for Fractured Wells. SPE 7490, Richardson, Texas: Society of Petroleum Engineers, American Institute of Mining, Metallurgical and Petroleum Engineers.

Cinco-Ley, H & Samaniego, V (1981b). Transient Pressure Analysis: Finite Fracture versus Damaged Fracture case. SPE 10179, Richardson, Texas: Society of Petroleum Engineers, American Institute of Mining, Metallurgical and Petroleum Engineers.

Constitution of South Africa (1996). *Government Gazette*. Act 108, 1996. Pretoria, South Africa.

Department of Water Affairs and Forestry (1996). South African Water Quality Guidelines, Volume 7: Aquatic Ecosystems. Private Bag X313, Pretoria.

Doll, R and Peto, R (1981). The Causes of Cancer. Journal of National Cancer Institute, vol 66, p 1193 – 1308.

Draft National Health Bill (2001). *Government Gazette*. Pretoria, South Africa.

Environmental Conservation Act (1989). *Government Gazette*. Act 73, 1989. Pretoria, South Africa.

Environmental Protection Agency (2001). Well Head Protection Areas. Available on Internet at http://www.wrds.uwyo.edu/wrds/deq/whp/whpsect2.html.

Environmental Protection Agency (2000). Drinking water standards and health advisories. EPA 822-B-00-001. Office of Water. US Environmental Protection Agency, Washington D.C.

Environmental Protection Agency (1994). Estimating radiogenic cancer risks. EPA 402-R-93-076. 401 M Street SW, Washington.

Environmental Protection Agency (1994a). Cancer risk coefficient for environmental exposure to radionuclides. Federal Guidance report no 13. EPA 402-R-99-001. Office of Radiation and Indoor Air, Washington, DC.

Environmental Protection Agency (1989). Risk assessment guidance for Superfund, vol 1. Human health manual (part A), Rep EPA/540/1-89/002. Office of Emergency and Remedial Response, Washington, D.C.

Environmental Protection Agency (1988). IRIS: Integrated Risk Information System. IRIS user support, EPA office of research and development, Environmental Criteria and Assessment Office (MS-190), Cincinnati. Available on Internet at http://www.epa.gov/.

Feenstra, S, Cherry, JA, Sudicky, EA and Haq, Z (1984). Matrix Diffusion Effects on Contaminant Migration from an Injection Well in Fractured Sandstone. GROUND WATER, vol 22, p 307 – 316.

Fetter, CW (1999). Contaminant Hydrogeology, second edition. Prentice-Hall, Inc. New Jersey.

Foster, SSD (1975). The chalk groundwater tritium anomaly – a possible explanation. Journal of Hydrology, vol 25, p 289 – 299.

Freeze, RA and Cherry, JA (1979). Groundwater. Prentice-Hall, Englewood Cliffs, N.J.

Freeze, A, Massmann, J, Smith, L, Sperling, T and James, B (1990). Hydrogeological Decision Analysis: 1.A Framework. GROUND WATER, vol, 28, no 5, p 738 – 766.

Genthe, B and Rodda, N (1999). Application of Health Risk Assessment Techniques to Microbial Monitoring Data. Water Research Commission Report No 470/1/99, Pretoria.

Genthe, B (1998). Health Risk Assessment Training Workshop. Enivironmentek, CSIR, Stellenbosch.

Gringarten, AC, Ramey Jr, HJ, & Raghavan, R (1974). Unsteady-state pressure distribution created by a well with a single infinite-conductivity vertical fracture. SPE 4051, In Proceedings of SPE-AIME 47th Annual Fall Meeting, San Antonio, Texas, Oct. 8-11, 1972. Richardson, Texas: Society of Petroleum Engineers, American Institute of Mining, Metallurgical and Petroleum Engineers.

Grobbelaar, R (2000). The long-term impact of intermine flow from collieries in the Mpumalanga coalfields. MSc thesis, Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Hatton, T and Evans, R (1998). Dependence of Ecosystems on Groundwater and its Significance to Australia. Occasional Paper No 12/8. Land and Water Resources, CSIRO, Australia.

Hoag, RS and Price, JS (1997). The effects of matrix diffusion on solute transport and retardation in undisturbed peat in laboratory columns. Journal of Contaminant Hydrology, vol 28, p 193 – 205.

Hodgson, FDI (2001). Personal communication. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Hughes, DA (1999). SARES. Institute for Water Research, Rhodes University, Grahamstown, South Africa.

Hurst, HE (1957). The Nile: A general account of the river and the utilization of its water. Constable and Company Ltd., London.

Janse Van Rensburg, H (1992). Gehidrologiese Besluitnemingsanalise – 'n koste, voordeel- en risokobenadering. Graduate School of Business Leadership, University of South Africa, Pretoria.

Kruseman, GP and De Ridder, NA (1991). Analysis and Evaluation of Pumping Test Data, second edition. International Institute for Land Reclamation and Improvement, PO Box 45, 6700 AA Wageningen, The Netherlands.

Lynch, SD, Reynders, AG and Schulze, RE (1994). Preparing input data for a national-scale groundwater vulnerability map of Southern Africa. Water SA vol 20, no 3, p 239 – 246.

MacKay, HM (1998). Towards a classification system for water resources in South Africa. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria.

Maloszewski, P and Zuber A (1993). Tracer Experiments in Fractured Rocks: Matrix Diffusion and the Validity of Models. Water Resources Research, vol 29, p 2723 – 2735.

Maxwell, RM, Pelmulder, SD, Tompson, AFB and Kastenberg, WE (1998). On the development of a new methodology for groundwater driven risk assessment. Water Resources Research, vol 34, no 4, p 833 – 847.

Mazurek, JV (1996). The Role of Health Risk Assessment and Cost-Benefit Analysis in Environmental Decision Making in Selected Countries. Available on the Internet at http://www.rff.org.

Merrick, NP (2000). Assessing uncertainty in sustainable yield. In proceedings of GROUNDWATER: Past Achievements and Future Challenges, Cape Town, p 401 – 405.

Misstear, BDR (2001). The values of simple equilibrium approximations. Hydrogeology Journal, vol 9, no 2, p 125 – 126.

Moench, AF (1984). Double-Porosity Models for Fissured Groundwater Reservoir with Fracture Skin. Water Resources Research, vol 20, p 831-846.

National Environmental Act (1998). *Government Gazette*. Act 107, 1998. Pretoria, South Africa.

National Water Act (1998). *Government Gazette*, 19182. Act 36, 26 August 1998. Pretoria, South Africa.

Peters, EE (1996). Chaos and order in the capital markets. Second Edition. John Wiley and Sons, Inc. United States of America.

Quality of Domestic Water Supplies, Volume 1: Assessment Guide (2001). Report no TT 101/98, Water Research Commission, Pretoria.

Rose, JB and Gerba, CP (1991). Use of risk assessment for development of microbial standards. Water Science Technology, vol 24, no 2, p 29 – 34.

Rosen, L (1994). A study of the DRASTIC methodology with emphasis on Swedish conditions. GROUND WATER, vol 32, no 2, p278 – 285.

Rosen, L and LeGrand, HE (1997). An Outline of a Guidance Framework for Assessing Hydrogeological Risks at Early Stages. GROUND WATER, vol 35, p 195 – 204.

Rosen, L, Wladis, D and Ramaekers, D (1998). Risk and decision analysis of groundwater protection alternatives on the European scale with emphasis on nitrate and aluminium contamination from diffuse sources. Journal of Hazardous Materials vol 61, p 329 – 336.

Ross, B and Lu, N (1999). Dynamics of DNAPL penetration into fractured porous media. GROUND WATER vol 37, p 140 – 147.

Schwab, M and Genthe, B (1998). Environmental Health Risk Assessment: A primer for South Africa. Environmentek, CSIR, PO Box 320, Stellenbosch, South Africa.

Scott, DF and Le Maitre, DC (1998). The Interaction between Vegetation and Groundwater: Research Priorities for South Africa. Water Research Commission Report No 730/1/98, Pretoria.

Sharp, JM (1998). Sustainable Groundwater Supplies – an evolving issue: Examples from Major Carbonate Aquifers of Texas USA. In proceedings of Groundwater: Sustainable Solutions, University of Melborne, Melborne, Australia.

Spitz, K and Moreno, J (1996). A practical guide to groundwater and solute transport modelling. John Wiley and Sons, Inc. United States of America.

Sugeno, M (1985). An introductory survey of fuzzy control. Information Sciences vol 36, p 59 – 83.

Van der Werf, HMG. and Zimmer, C (1997). An indicator of pesticide environmental impact based on a fuzzy expert system. INRA, Station d'Agronomie, 28 rue de Herrlisheim, BP 507, 68021, Colmar, France. Available on the Internet at http://www.pmac.net/benbfuz1.htm.

Van Tonder GJ, Kunstmann, H and Xu, Y (1999). Estimation of the Sustainable Yield of a Borehole Including Boundary Information, Drawdown Derivatives and Uncertainty Propagation. Institute for Groundwater Studies, University of the Free State, PO Box 339, Bloemfontein.

Van Tonder, GJ and Dennis, I (2000). Catchment, aquifer and groundwater balance. In proceedings: Course on Ground Water and the National Water and Water Services Acts, University of Pretoria Conference Centre, Pretoria.

Van Tonder, GJ (2001). Geohydrology Course notes, University of the Free State, PO Box 339, Bloemfontein, 9300.

Van Tonder, GJ (2001a). Personal communication. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Van Tonder GJ, Riemann, K and Dennis, I (2001). Interpretation of single-well tracer tests using fractional flow dimensions, Part 1: Theory and mathematical models. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Van Tonder GJ and Xu, Y (2001). A Guide for the estimation of groundwater recharge in South Africa. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Vegter, JR (1995). An Explanation of a Set of National Groundwater Maps, WRC report TT 74/95, Water Research Commission, Pretoria.

Vegter, JR and Pitman, WV (1996). Recharge and streams: Paper presented at the workshop on groundwater-surface water issues in arid and semi-arid areas.

Vivier, JJP, Van Tonder, GJ and Botha, JF (1995). The use of slug tests to predict borehole yields: correlation between the recession time of slug tests and borehole yields. In proceedings: Groundwater '95 – Groundwater recharge and rural water supply, Volkswagen Conference Centre, Midrand, South Africa.

Water Services Act (1997). *Government Gazette*, 18522. Act 108, 19 December 1997. Cape Town, South Africa.

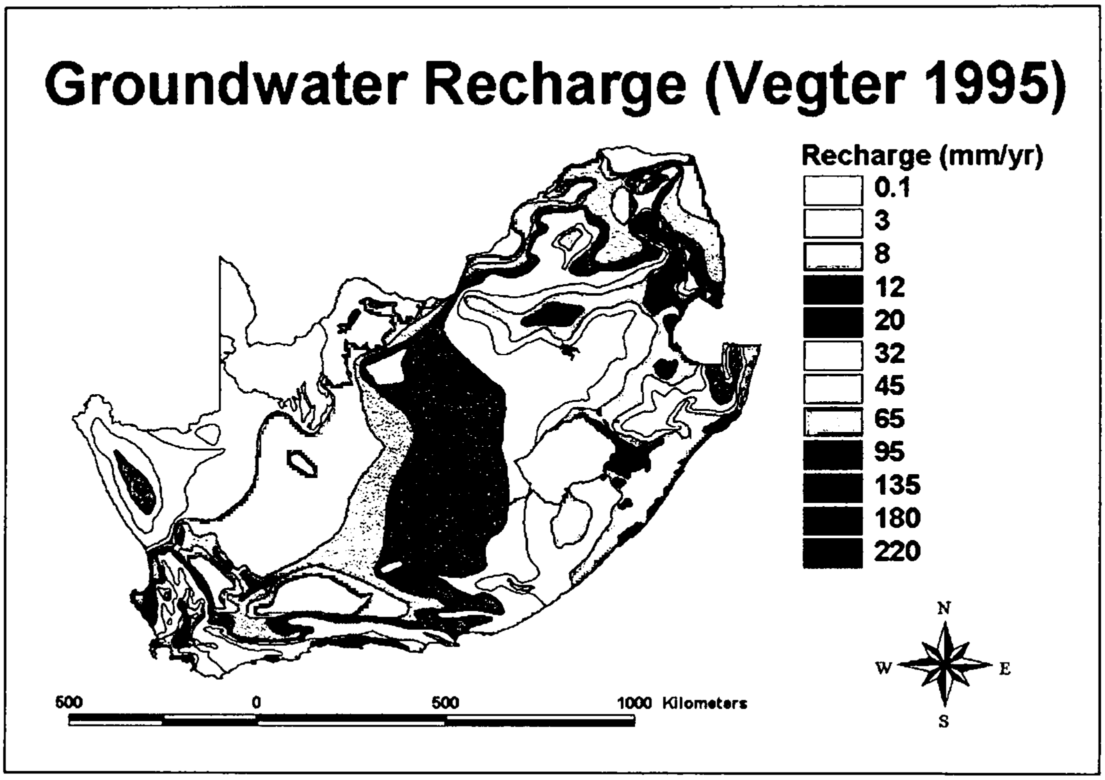
Yamaguchi, T, Sakamoto, Y, Nakayama, S and Vandergraaf, TT (1997). Effective diffusivity of the uranyl ion in a granite from Inada, Ibaraki, Japan. Journal of Contaminant Hydrology, vol 26, p 109 – 117.

Zadeh, LA (1965). Fuzzy Sets. Information and Control vol 8, p 338 – 353.

APPENDIX A

Groundwater Sustainability Risk Assessment Information

A1. VEGTER'S GROUNDWATER RECHARGE MAP



A2. STORATIVITY VALUES AND AQUIFER TYPES

The storativity values given to the various aquifer types were determined by G van Tonder, and are listed in the table below:

Aquifer type	Storativity value
Fractured hard rock	1×10^{-3}
Karoo fractured rock	3×10^{-3}
Table mountain group	8×10^{-3}
Dolomite	1×10^{-2}
Porous	1×10^{-1}

A3. CALCULATIONS OF BOUNDARY CONDITIONS FOR THE INTERMEDIATE AND COMPREHENSIVE SUSTAINABLE RISK CALCULATION *(Taken directly from Van Tonder et al., 1999)*

1. Extrapolation of Pumping Test Drawdown

The extrapolation of the drawdown of the pumping test is the sum of the drawdown that is due to the production well, s_{Well}, and the boundaries, $s_{Boundary}$:

Eq. 1: $$s(t = t_{long}) = s_{Well} + s_{Boundary}$$

The following sections distinguish between the extrapolation of s_{Well} and $s_{Boundary}$.

1.1 Extrapolation of Production Well Drawdown

The drawdown that is due to the production well is extrapolated by a Taylor series expansion around the late measurement points of the drawdown at $t \approx t_{EOP}$ (subscript EOP denotes end of pumping test). The Taylor series expansion is performed with respect to the logarithm of time, $\log_{10}$. A second order approximation is assumed to be sufficient:

Eq. 2:

$$s_{Well}(t = t_{long}) \approx s(t = t_{EOP}) + \frac{\partial s}{\partial \log t}\bigg|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP}) + $$
$$+ \frac{1}{2}\frac{\partial^2 s}{\partial(\log t)^2}\bigg|_{t=t_{EOP}} (\log t_{long} - \log t_{EOP})^2$$

The time t_{EOP} must be large enough to ensure that the drawdown has already passed the early time flow behavior that is due to well bore storage, fracture flow and double porosity effects. This can clearly be monitored by looking at the derivative plot $\partial s / \partial \log t$. Usually the effect of the boundaries can only be seen at very late times of the pumping test. For simple geometries of the boundaries, image well theory can be applied to analyse the effect of the boundaries on the drawdown. This is shown in the following section.

1.2 Extrapolation of the Boundary Drawdown

Four simplified cases of no-flow boundaries are investigated:

- A single barrier boundary
- Two barrier boundaries intersecting at 90^0
- Two parallel boundaries
- A closed square barrier boundary

- **Single barrier boundary**

The single barrier boundary is illustrated in Fig.1:

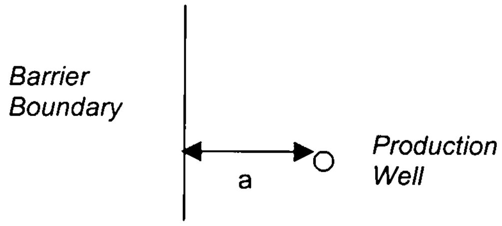


Fig. 1: Single Barrier Boundary

The influence of the barrier boundary can be described by constructing an image well. This image well is located on the other side of the boundary at the same distance as from the boundary to the pumping well. The drawdown in the pumping well due to the barrier boundary is expressed by

Eq. 3 $$s_{Boundary}(t) = \frac{Q}{4\pi T} W(u_{2a})$$

with $u_{2a} = \frac{S \cdot (2a)^2}{4Tt}$.

Usually the distance *a* between the pumping well and the boundary is large compared with the effective borehole radius *r*. At early times t, u_{2a} is large against u_r of the Theis equation. Since the well function W(u) is small at large $u=u_{2a}$, $s_{Boundary}$ does not contribute significantly to the total drawdown $s_{total}=s_{Well}+s_{Boundary}$ at early times.

- **Two barrier boundaries intersecting at 90^0**

The case of perpendicular barrier boundaries is illustrated in Fig. 2:

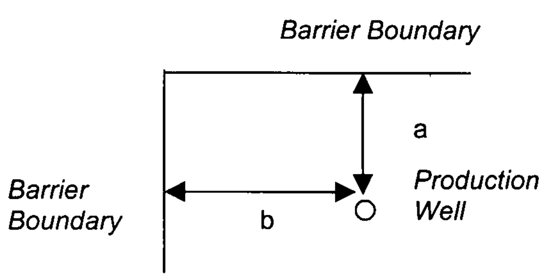


Fig. 2: Two Barrier Boundaries Intersecting at 90^0

In this case three image wells are needed to describe the drawdown in the pumping well. The drawdown due to the three image wells is expressed by the following equation:

Eq. 4 $$s_{Boundary}(t) = \frac{Q}{4\pi T}\{W(u_{2a}) + W(u_{2b}) + W(u_{2c})\}$$

with $u_{2a} = \frac{S \cdot (2a)^2}{4Tt}$, $u_{2b} = \frac{S \cdot (2b)^2}{4Tt}$, $u_{2c} = \frac{S \cdot (2c)^2}{4Tt}$, $2c = \sqrt{(2a)^2 + (2b)^2}$.

- **Two parallel boundaries**

In the case of two parallel boundaries (Fig. 3), an infinite number of image wells is necessary to account for the drawdown due to the boundary.

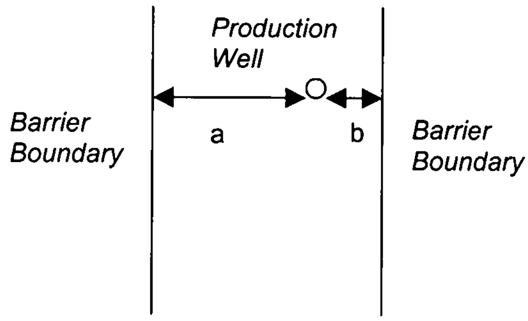


Fig. 3: Two Parallel Barrier Boundaries

The following formula approximates the influence of the boundaries by taking into account the eight closest image wells:

Eq.5

$$s_{Boundary}(t) \approx \frac{Q}{4\pi T}\{W(u_{2a}) + W(u_{2b}) + 2W(u_{2a+2b}) + W(u_{2a+4b}) + W(u_{4a+2b}) + 2W(u_{4a+4b})\}$$

with $u_{2a} = \frac{S \cdot (2a)^2}{4Tt}$, $u_{2b} = \frac{S \cdot (2b)^2}{4Tt}$, $u_{2a+2b} = \frac{S \cdot (2a+2b)^2}{4Tt}$, etc.

- **Closed square boundary**

A closed square aquifer is described as surrounded by barrier boundaries (Fig. 4).

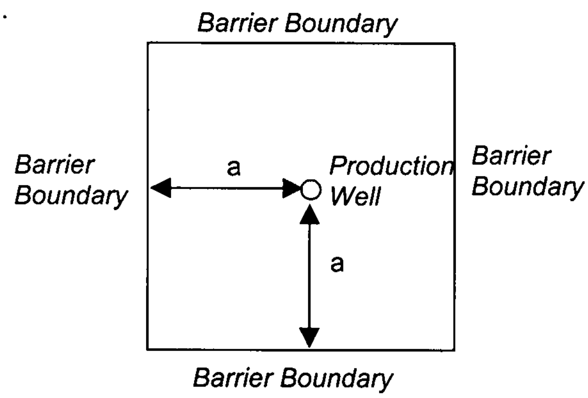


Fig. 4: Closed Square Barrier Boundary

The solution can be approximated by

Eq. 6 $$s_{Boundary}(t) \approx \frac{Q}{4\pi T}\{W(u_{2a}) + W(2u_{2a})\} \text{ for } \frac{Tt}{Sa^2} < \frac{1}{\pi}$$

Eq. 7

$$s_{Boundary}(t) \approx \frac{Q}{4\pi T}\{-2.6084 - \frac{4}{\pi}\frac{3}{2}e^{-\frac{Tt\pi^2}{Sa^2}} + \frac{Tt\pi}{Sa^2} + 2\ln[\frac{2a}{r}]\} \text{ for } \frac{1}{\pi} \le \frac{Tt}{Sa^2} < 1$$

and

Eq. 8 $$s_{Boundary}(t) \approx \frac{Q}{4\pi T}\{-2.6084 + \frac{Tt\pi}{Sa^2} + 2\ln[\frac{2a}{r}]\} \text{ for } \frac{Tt}{Sa^2} \ge 1$$

A4. RECHARGE CALCULATIONS: THE CHLORIDE AND EARTH METHODS

(Taken directly from Van Tonder and Xu, 2001)

1. The Chloride Method

General Equation: $R = (P\ Cl_p + D)/Cl_w$

[R = recharge (mm/a); P = mean annual precipitation (mm/a); Cl_p = chloride in rain (mg/l); D = dry chloride deposition (mg/m^2/a); Cl_w = chloride concentration (mg/l) in soil water below active root zone in unsaturated zone OR Cl_w = chloride concentration (mg/l) of groundwater where for many boreholes the Cl_{gw} = harmonic mean of the Cl content in the boreholes].

Assumptions: The assumptions necessary for successful application are that (1) there is no source of chloride in the soil water or groundwater other than that from precipitation, (2) chloride is conservative in the system, (3) steady-state conditions are maintained with respect to long-term precipitation and chloride concentration in that precipitation, and in the case of the unsaturated zone, (4) a piston flow regime, which is defined as downward vertical diffuse flow of soil moisture, is assumed. However, this assumption may be invalidated if the flow through the unsaturated zone is along preferred pathways.

2. The EARTH Method

EARTH= Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hardrock
General Equation: Sdh/dt=R-h/DR
[R = recharge (m^3/month); S = specific yield and dh/dt = change in water level head during one month; DR=drainage resistance (a site specific parameter); h=groundwater level]
Equation 1: Linear transfer function: $h_i = h_{i-1} - \Delta t\, h_{i-1}/DR + \Delta t\, R_i/S$
$DR = L^2/\beta T$, L=length of flow path; β=2 for radial and =4 for parallel flow; T=transmissivity
Δt=time interval (1 month)
To obtain unique fit, the value of S must be known a priori
Data Requirements
• Monthly water levels and precipitation

A5. EQUATIONS FOR MEMBERSHIP FUNCTIONS FOR THE SUSTAINABLE RISK ASSESSMENT

Membership functions for blow yield, storativity and recharge are cosine graphs in the form:

$$\text{Membership} = \left[\frac{1}{2} \times (\cos(((I - U) * \pi / \text{stretch}) - \pi) + 1)\right]$$

where

Membership = A value between 0 and 1

I = Input (the value given by the user/calculated by the DT for blow yield, storativity or recharge)

U = Unfavourable limit

Stretch = Absolute value (favourable limit – unfavourable limit)

The membership function for the pumping rate is:

$$\text{Membership} = 1 - \left[\frac{1}{2} \times (\cos(((I - F) * \pi / \text{stretch}) - \pi) + 1)\right] \text{ where}$$

I = Input (the value given by the user for pumping rate)

F = Favourable limit

The membership function for drawdown is calculated by firstly determining the power n from the following equation:

$$n = \frac{\log 0.5}{\log\left(\frac{x}{U}\right)}$$

where

$$x = 0.7U + \left(\frac{1.7(U-10)}{10}\right)$$

The membership function can now be determined as:

$$\text{Membership} = 1 - \left(\frac{I}{U}\right)^n$$

where

I = Drawdown determined by DT.

A6. IMPORTED PUMPING TEST DATA FOR BOREHOLE UO5

Pumping test data is stored in comma deliminated *.ddn file. The format of the file is:

Q (pumping rate in L/s)

Time (min), drawdown (m) or waterlevels (m) x n

where n is the number of observations

The UO5.ddn file used in the intermediate sustainability assessment:

1.25	
1.5	0.20893
2	0.274838
2.5	0.333399
3	0.382644
3.5	0.425234
4	0.460503
4.5	0.494442
5	0.525719
5.5	0.553669
6	0.580953
6.5	0.603579
7.5	0.650827
8.5	0.699406
9.5	0.74133
10.5	0.778597
11.5	0.816528
12.5	0.850467
13.5	0.883075
14.5	0.91169

15.5	0.942967
16.5	0.966258
17.5	0.995539
18.5	1.020161
19.5	1.042787
20.5	1.065413
21.5	1.088039
22.5	1.109999
23.5	1.131294
24.5	1.150593
25.5	1.16856
26.5	1.188524
27.5	1.205827
28.5	1.223794
29.5	1.242427
30.5	1.254406
31.5	1.265053
32.5	1.287679
33.5	1.300323
34.5	1.313632
35.5	1.327607
36.5	1.339585
37.5	1.351564
38.5	1.362877
39.5	1.379513
40.5	1.390826
41.5	1.401474
42.5	1.413452
43.5	1.422769
44.5	1.432751
45.5	1.442067
46.5	1.449388
47.5	1.45937
48.5	1.468021
49.5	1.474675
50.5	1.485323
51.5	1.492643
52.5	1.499963
53.5	1.508614
54.5	1.515269
55.5	1.52392
56.5	1.530575
57.5	1.537229
58.5	1.544549
59.5	1.551204
60.5	1.556528
61.5	1.564513
62.5	1.572499
63.5	1.579819
64.5	1.585143
65.5	1.592463
66.5	1.599783
67.5	1.605107
68.5	1.613092
69.5	1.618416
70.5	1.624405
71.5	1.628398
72.5	1.631726
73.5	1.641708
74.5	1.648362
75.5	1.65169
76.5	1.657679

77.5	1.665664
78.5	1.670323
79.5	1.676977
80.5	1.682301
81.5	1.68829
82.5	1.694945
83.5	1.697607
84.5	1.704261
85.5	1.711582
86.5	1.714243
87.5	1.721564
88.5	1.725556
89.5	1.731546
90.5	1.735538
91.5	1.741528
92.5	1.746186
93.5	1.753506
94.5	1.757499
95.5	1.762157
96.5	1.767481
97.5	1.77347
98.5	1.778794
99.5	1.783452
100.5	1.788776
110.5	1.8307
120.5	1.886599
130.5	1.935179
140.5	1.979765
150.5	2.019027
160.5	2.056959
170.5	2.094891
180.5	2.128164
190.5	2.15811
200.5	2.189387
210.5	2.210682
220.5	2.234639
230.5	2.271239
240.5	2.305178
250.5	2.329801
260.5	2.353757
270.5	2.367732
280.5	2.394351
290.5	2.418973
300.5	2.438937
310.5	2.460232
320.5	2.482858
330.5	2.510142
340.5	2.532103
350.5	2.556725
360.5	2.576689
370.5	2.598649
380.5	2.617282
390.5	2.640574

A7. FORMAT OF IMPORTED GEOGRAPHICAL DATA FILES

Borehole data is stored in comma deliminated *.bhl file. The file format is:

Number, name, x-coordinate, y-coordinate x n where n is the number of boreholes

The Campus test site boreholes *.bhl file is:

1	UO1	-78888.7	-21052.1
2	UO2	-78883.6	-21055.4
3	UO3	-78892.4	-21066.2
4	UO4	-78892.9	-21068.9
5	UO5	-78893.6	-21071
6	UO6	-78894.6	-21076.3
7	UO7	-78899.4	-21075
8	UO8	-78898.4	-21069.8
9	UO9	-78897.1	-21065.4
10	UO10	-78844.7	-21066.7
11	UO11	-78868.3	-21102.4
12	UO12	-78887.5	-21135.7
13	UO13	-78910.8	-21044.9
14	UO14	-78919.3	-21070.9
15	UP15	-78898.7	-21092.9
16	UP16	-78912.1	-21097.8
17	UO17	-78878	-21057.1
18	UO18	-78875.6	-21080.2
19	UO19	-78893.4	-21113.8
20	UO20	-78909.8	-21072.8
21	UO21	-78996.8	-21051.5
22	UO22	-78954.1	-21165.5
23	UO23	-78967	-21136
24	UO24	-78990	-21165

Boundary data is stored in comma deliminated *.brd file. The file format is:

Boundary type (will always be NOFLOW)

x-coordinate, y-coordinate x n (where n is the number of points given for the boundary)

END

The example discussed in Chapter 4 does not have a boundary file.

A8. FORMAT OF INPUT FILE FOR EARTH MODEL

Water level data is stored in comma deliminated *.rwl file. The file format is:

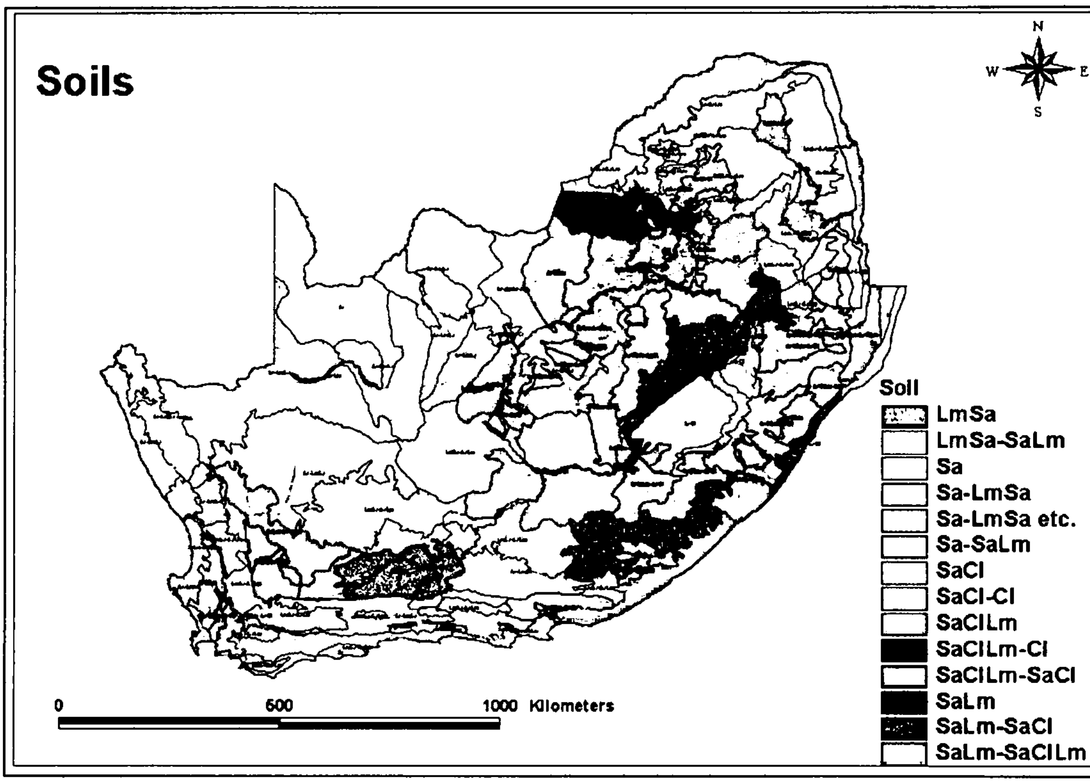
Month no, water level (m) x n

where n is the number of water level readings

APPENDIX B

Groundwater Contamination Risk Assessment Information

B1. SOILS MAP



Where

Sa = Sand

Lm = Loam

Cl = Clay

B2. WATER QUALITY GUIDELINES

Drinking Water Guidelines *(Taken from Quality of Domestic Water Supplies, 2001)*

Contaminant (mg/L)	Unacceptable (1.0)	Poor (0.75)	Marginal (0.5)	Good (0.25)	Ideal (0.0)
Arsenic	>2	0.2 - 2	0.05 - 0.2	0.01 - 0.05	<0.010
Cadmium	> 0.05	0.02 - 0.05	0.005 - 0.02	0.003 - 0.005	<0.003
Calcium		>300	150 - 300	80 - 150	<80
Chloride	> 1200	600 - 1200	200 - 600	100 - 200	< 100
Copper	> 15	20 - 15	1.3 - 2	1 - 1.3	< 1
Fluoride	> 3.5	1.5 - 3.5	1 - 1.5	0.7 - 1	< 0.7
Iron	> 10	2 - 5	1 - 2	0.5 - 1	< 0.5
Magnesium	> 400	200 - 400	100 - 200	70 - 100	< 70
Manganese	> 10	4 - 10	0.4 - 4	0.1 - 0.4	< 0.1
Nitrate/Nitrite	> 40	20 - 40	10 - 20	6 - 10	< 6
Potassium	> 500	100 - 500	50 - 100	25 - 50	< 25
Sodium	> 1000	400 - 1000	200 - 400	100 - 200	< 100
Sulphate	> 1000	600 - 1000	400 - 600	200 - 400	< 200
Zinc				> 20	< 20

Numbers in brackets refers to membership values

As the domestic water guidelines are limited, numerous other drinking water guidelines were included:

- World Health Organisation
- South African
- US Environmental Protection Agency
- Australian
- European Economic Community

These guidelines are available on the following web sites:

- www.waterquality.Cr.org.au/guide.htm
- http://www.ehl.cc/pdf/TGWD-revised.pdf

As some of the values vary, the lowest value from all the guidelines was chosen for the ideal and unacceptable limits. These are documented in the following table. As they are not classified as the domestic water guidelines, cosine membership functions will be used to determine the degree of membership for each contaminant. Therefore only the unacceptable and ideal values are listed in the table.

Contaminant	Measuring unit	Lower limit (ideal)	Upper limit (unacceptable)
Micro elements:			
Antimony	ug/L	50	100
Arsenic	ug/L	10	300
Beryllium	ug/L	2	5
Bismuth	ug/L	250	500
Cadmium	ug/L	5	20
Chromium	ug/L	50	200
Cobalt	ug/L	250	500
Cyanide	ug/L	200	300
Gold	ug/L	2	5
Lead	ug/L	10	100
Mercury	ug/L	1	10
Molybdenum	ug/L	50	100
Nickel	ug/L	250	500
Selenium	ug/L	20	100
Silver	ug/L	20	50
Tellurium	ug/L	2	5
Thallium	ug/L	5	10
Tin	ug/L	100	200
Titanium	ug/L	100	500
Tungsten	ug/L	100	500
Vanadium	ug/L	100	500
Micro elements:			
Antimony	ug/L	0	50
Arsenic	ug/L	0	100
Beryllium	ug/L	0	2
Bismuth	ug/L	0	250
Cadmium	ug/L	0	10
Chromium	ug/L	0	50
Cobalt	ug/L	0	250
Cyanide	ug/L	0	200
Gold	ug/L	0	2
Lead	ug/L	0	50
Mercury	ug/L	0	5
Molybdenum	ug/L	0	50
Nickel	ug/L	0	250
Selenium	ug/L	0	20
Silver	ug/L	0	50
Tellurium	ug/L	0	2
Thallium	ug/L	0	5
Tin	ug/L	0	100
Titanium	ug/L	0	100
Tungsten	ug/L	0	100
Vanadium	ug/L	0	250
Macro elements:			
Aluminium	mg/L	0	0.15
Ammonia	mg/L	0	1

Barium	mg/L	0	0.5
Boron	mg/L	0	0.5
Bromide	mg/L	0	1
Calcium	mg/L	0	150
Chloride	mg/L	0	250
Copper	mg/L	0	0.5
Fluoride	mg/L	0	1
Iodide	mg/L	0	0.5
Iron	mg/L	0	0.1
Lithium	mg/L	0	2.5
Magnesium	mg/L	0	70
Manganese	mg/L	0	0.05
Nitrate	mg/L	0	6
Nitrite	mg/L	0	0.03
Nitrate/Nitrite	mg/L	0	6
Posphorus	mg/L	0	5
Potassium	mg/L	0	200
Sodium	mg/L	0	100
Sulphate	mg/L	0	200
Surfactants	mg/L	0	0.2
Uranium	mg/L	0	1
Zinc	mg/L	0	1
Non-Specific Organic Measurement:			
Total Trihalomethanes	ug/L	0	100
Disinfection By-products:			
Bromodichloromethane	ug/L	0	60
Bromoform	ug/L	0	100
Chloroform	ug/L	0	200
Dibromoacetonitrile	ug/L	0	100
Dibromochloromethane	ug/L	0	100
Dichloroacetate	ug/L	0	53
Dichloroacetonitrile	ug/L	0	90
Dichloroacetic Acid	ug/L	0	50
Formaldehyde	ug/L	0	900
Trichloroacetate	ug/L	0	105
Trichloroacetic Acid	ug/L	0	100
Trichloroacetaldehyde	ug/L	0	10
Trichloroacetonitrile	ug/L	0	1
Trichlorophenol 2,4,6-	ug/L	0	200
Chlorinated organics:			
Carbon Tetrachloride	ug/L	0	2
Dichlorobenzene 1,2-	ug/L	0	1000
Dichlorobenzene 1,4-	ug/L	0	300
Dichloroethane 1,2	ug/L	0	30
Dichloroethane 1,1	ug/L	0	30
Dichloroethene 1,2-	ug/L	0	50
Dichloroethene 1,2-(Trans)	ug/L	0	100
Dichloroethene 1,2-(Cis)	ug/L	0	50

Dichloromethane	ug/L	0	20
Monochlorobenzene	ug/L	0	300
Tetrachloroethene	ug/L	0	40
Total Trichlorobenzene 1,2,4-	ug/L	0	20
Trichloroethane 1,1,1,-	ug/L	0	200
Trichloroethene 1,1,2,-	ug/L	0	70
Vinyl Chloride	ug/L	0	5
Aromatic Hydrocarbons:			
Benzene	ug/L	0	10
Benzo(a)Pyrene	ug/L	0	0.7
Ethylbenzene	ug/L	0	300
Styrene	ug/L	0	20
Toluene	ug/L	0	700
Xylene	ug/L	0	500
Miscellaneous Organic:			
Acrylamide	ug/L	0	0.5
Diethylhexyladipate	ug/L	0	80
Diethylhexylphthalate	ug/L	0	8
EDTA	ug/L	0	200
Hexachlorobutadiene	ug/L	0	0.6
Hexachlorocyclopentadiene	ug/L	0	50
Nitrilotriacetic Acid	ug/L	0	200
PCBS	ug/L	0	0.5
Tributylin Oxide	ug/L	0	2
Phenols	ug/L	0	0.5
PAH	ug/L	0	0.2
Pesticides:			
Acephate	ug/L	0	0.1
Adipate	ug/L	0	500
Alachlor	ug/L	0	20
Aldicarb	ug/L	0	10
Aldicarb Sulphone	ug/L	0	2
Aldicarb Sulphoxide	ug/L	0	4
Aldrin & Dieldrin	ug/L	0	0.03
Aldrin	ug/L	0	0.03
Amitrole	ug/L	0	1
Asulam	ug/L	0	100
Atrazine	ug/L	0	2
Azinphos-methyl	ug/L	0	10
Barban	ug/L	0	300
Benomyl	ug/L	0	200
Bentazone	ug/L	0	30
Bioresmethrin	ug/L	0	60
Bromacil	ug/L	0	600
Bromoxynil	ug/L	0	30
Bromophos-ethyl	ug/L	0	20
Carbaryl	ug/L	0	60
Carbendazim	ug/L	0	200
Carbofuran	ug/L	0	5

Carbophenthion	ug/L	0	1
Chlordane	ug/L	0	0.2
Chlordimeform	ug/L	0	20
Chlorfenvinphos	ug/L	0	10
Chloroxuron	ug/L	0	30
Chlorphyrifos	ug/L	0	2
Chlortoluron	ug/L	0	30
Cyanazine	ug/L	0	10
Cyhexatin	ug/L	0	200
Dalapon	ug/L	0	200
DDT	ug/L	0	2
Demeton	ug/L	0	30
Diazinon	ug/L	0	10
Dibromo-3-chloropropane 1,2-	ug/L	0	1
Dicamba	ug/L	0	300
Dichlobenil	ug/L	0	20
Dichlorprop	ug/L	0	100
Dichloropropane 1,2-	ug/L	0	20
Dichloropropene 1,3-	ug/L	0	20
Dichlorvos	ug/L	0	20
Diclofop-methyl	ug/L	0	3
Dicofol	ug/L	0	100
Dieldrin	ug/L	0	1
Difenzoquat	ug/L	0	200
Dimethoate	ug/L	0	100
Dinoseb	ug/L	0	7
Diquat	ug/L	0	100
Disulfoton	ug/L	0	6
Diuron	ug/L	0	40
DPA	ug/L	0	500
Endosulfan	ug/L	0	40
Endothall	ug/L	0	100
Endrin	ug/L	0	1
EPTC	ug/L	0	60
Ethion	ug/L	0	6
Ethoprophos	ug/L	0	1
Ethylene Dibromide (EDB)	ug/L	0	0.1
Fenchlorphos	ug/L	0	60
Fenitrothion	ug/L	0	20
Fenoprop	ug/L	0	9
Fensulfothion	ug/L	0	20
Fenvalerate	ug/L	0	40
Flamprop-methyl	ug/L	0	6
Fluometuron	ug/L	0	100
Formothion	ug/L	0	100
Fosamine (Ammonium salt)	ug/L	0	3000
Glyphosate	ug/L	0	700
Heptaclor	ug/L	0	3
Heptaclor Epoxide	ug/L	0	0.03

Hexachlorobenzene	ug/L	0	1
Hexaflurate	ug/L	0	60
Hexazinone	ug/L	0	600
Isoproturan	ug/L	0	9
Lindane	ug/L	0	2
Maldison	ug/L	0	100
MCPA	ug/L	0	2
Metolachlor	ug/L	0	800
Mecoprop (MCPP)	ug/L	0	10
Methidathion	ug/L	0	60
Methomyl	ug/L	0	60
Methoxychlor	ug/L	0	20
Metribuzin	ug/L	0	5
Mevinphos	ug/L	0	6
Molinate	ug/L	0	6
Monocrotophos	ug/L	0	2
Nabam	ug/L	0	30
Nitralin	ug/L	0	1000
Nitrilotriacetic Acid (NTA)	ug/L	0	50
Omethoate	ug/L	0	0.4
Oryzalin	ug/L	0	60
Oxamyl	ug/L	0	200
Paraquat	ug/L	0	40
Parathion	ug/L	0	30
Parathion-methyl	ug/L	0	6
Pendimethalin	ug/L	0	20
Pentachlorophenol	ug/L	0	9
Perfluidone	ug/L	0	20
Permethrin	ug/L	0	20
Picloram	ug/L	0	500
Piperonyl Butoxide	ug/L	0	200
Pirimicarb	ug/L	0	100
Primiphos-ethyl	ug/L	0	1
Primiphos-methyl	ug/L	0	60
Profenofos	ug/L	0	0.6
Promecarb	ug/L	0	60
Propanil	ug/L	0	20
Propargite	ug/L	0	1000
Propoxur	ug/L	0	1000
Pyrazophos	ug/L	0	6
Pyridate	ug/L	0	100
Quintoxene	ug/L	0	40
Simazine	ug/L	0	2
Sulprofos	ug/L	0	20
Temephos	ug/L	0	30
Thiobencarb	ug/L	0	40
Thiometon	ug/L	0	20
Thiophanate	ug/L	0	100
Thiram	ug/L	0	30

Toxaphene	ug/L	0	3
Trichlorfon	ug/L	0	10
Triclopyr	ug/L	0	20
Trifluralin	ug/L	0	20
2,3,7,8,-TCDD (Dioxin)	ug/L	0	0.00003
2,4,5,-T	ug/L	0	9
2,4,5,-TP (Silvex)	ug/L	0	9
Acetic Acid)	ug/L	0	30
Butanoic Acid)	ug/L	0	90
3,6-Dichloropicolinic Acid	ug/L	0	1000
Pesticide total	ug/L	0	100
Pesticide total (Herbicides & Fungicides)	ug/L	0	0.5

Rating for the rapid assessment where there are no concentrations

Contaminant	Rapid rating
2,3,7,8,-TCDD (Dioxin)	Effects common
2,4,5,-TP (Silvex)	Long-term effects
Acephate	Few effects
Acrylamide	Effects common
Aldicarb	Effects common
Aldrin & Dieldrin	Death
Aluminium	Long-term effects
Ammonia	Few effects
Antimony	Long-term effects
Arsenic	Death
Asbestos	Long-term effects
Atrazine	Long-term effects
Barium	Few effects
Bentazon	Few effects
Benzene	Death
Benzo(a)Pyrene	Effects common
Beryllium	Effects common
Boron	Few effects
Bromacil	Few effects
Bromate	Effects common
Bromodichloromethane	Few effects
Bromoform	Few effects
Cadmium	Long-term effects
Carbaryl	Effects common
Carbofuran	Effects common
Carbon Tetrachloride	Long-term effects
Chlordane	Death
Chlordimeform	Few effects
Chlorfenvinphos	Long-term effects
Chlorine	Death
Chlorine dioxide	Effects common
Chloroform	Few effects

Chlorphyrifos	Few effects
Chromium III	Few effects
Chromium VI	Long-term effects
Cobalt	Long-term effects
Copper	Few effects
Cyanide	Death
Cyhexatin	Few effects
DDT	Effects common
Diazinon	Death
Dibromo-3-chloropropane 1,2-	Few effects
Dicamba	Few effects
Dichloroacetic Acid	Death
Dichlorobenzene 1,2-	Long-term effects
Dichlorobenzene 1,4-	Long-term effects
Dichloroethane 1,1	Few effects
Dichloroethane 1,2	few effects
Dichloroethene 1,2-(Cis)	Long-term effects
Dichloromethane	Long-term effects
Dichloropropene 1,3-	Effects common
Dichlorvos	Few effects
Dicofol	Long-term effects
Dieldrin	Death
Dinoseb	Long-term effects
Diquat	Few effects
Disulfoton	Few effects
Diuron	Few effects
Endosulfan	Death
Endrin	Death
Ethylbenzene	Long-term effects
Ethylene Dibromide (EDB)	Effects common
Fluoride	Death
Formaldehyde	Few effects
Glyphosate	Few effects
Heptaclor	Effects common
Heptaclor Epoxide	Effects common
Hexachlorobenzene	Effects common
Hexachlorobutadiene	Few effects
Hexachlorocyclopentadiene	Effects common
Lead	Effects common
Lindane	Effects common
Manganese	Few effects
Mercury	Effects common
Methidathion	Effects common
Methoxychlor	Few effects
Metolachlor	Effects common
Metribuzin	Long-term effects
Molydbenum	Few effects
Monocrotophos	Few effects
Nickel	Few effects

Nitrate	Death
Nitrate/Nitrite	Death
Nitrite	Death
PAH	Effects common
Parathion	Death
PCBs	Long-term effects
Pentachlorophenol	Effects common
Phenols	Effects common
Piperonyl Butoxide	Few effects
Posphorus	Effects common
Propoxur	Effects common
Radon	Long-term effects
Selenium	Few effects
Silver	Few effects
Styrene	Few effects
Sulfate	Few effects
Thallium	Effects common
Thiram	Few effects
Tin	Few effects
Titanium	Effects common
Toluene	Long-term effects
Toxaphene	Few effects
Trichloroacetic Acid	Few effects
Trichloroethane 1,1,1,-	Effects common
Trichlorophenol 2,4,6-	Few effects
Trifluralin	Few effects
Uranium	Few effects
$Uranium^{238}$	Few effects
Vinyl Chloride	Effects common
Xylene	Effects common
Zinc	Few effects

Aquatic Ecosystem Guidelines *(Taken from DWAF, 1996)*

The Aquatic ecosystem guidelines for toxic constituents are list as follows:

Contaminant (ug/L)	TWQR	CEV	AEV
Acid soluble Aluminium	≤5	10	100
Un-ionised Ammonia	≤7	15	100
Total Arsenic	≤10	20	130
Atrazine	≤10	19	100
Total Cadmium	≤0.15	0.3	3
Total residual Chlorine	≤0.2	0.35	5
Dissolved Chromium(VI)	≤7	14	200
Dissolved Chromium(III)	≤12	24	340
Dissolved Copper	≤0.3	0.53	1.6
Free Cyanide	≤1	4	110
Endosulfan	≤0.01	0.02	0.2
Dissolved Fluoride	≤750	1500	2540
Dissolved Lead	≤0.2	0.5	4
Dissolved Manganese	≤180	370	1300
Total Mercury	≤0.04	0.08	1.7
Phenol	≤30	60	500
Total Selenium	≤2	5	30
Dissolved Zinc	≤2	3.6	36

Where

TWQR = Target water quality range

CEV = Chronic effect value

AEC = Acute effect value

B3. DIFFUSION VALUES

Parameter	Material	Diffusion Coefficient (m^2/s)	Source
H+	Water	9.31E-09	Spitz and Moreno, 1996
Na+	Water	1.33E-09	Spitz and Moreno, 1996
K+	Water	1.96E-09	Spitz and Moreno, 1996
Rb+	Water	2.06E-09	Spitz and Moreno, 1996
Cs+	Water	2.07E-09	Spitz and Moreno, 1996
Mg2+	Water	7.05E-10	Spitz and Moreno, 1996
Ca2+	Water	7.93E-10	Spitz and Moreno, 1996
Sr2+	Water	7.94E-10	Spitz and Moreno, 1996
Ba2+	Water	8.48E-10	Spitz and Moreno, 1996
Ra2+	Water	8.89E-10	Spitz and Moreno, 1996
Mn2+	Water	6.88E-10	Spitz and Moreno, 1996
Fe2+	Water	7.19E-10	Spitz and Moreno, 1996
Cr2+	Water	5.94E-10	Spitz and Moreno, 1996

Fe^{3+}	Water	6.07E-10	Spitz and Moreno, 1996
OH^-	Water	1.57E-09	Spitz and Moreno, 1996
F^-	Water	1.46E-09	Spitz and Moreno, 1996
Cl^-	Water	2.03E-09	Spitz and Moreno, 1996
Cl^-	Clay glacial	5.00E-10	Spitz and Moreno, 1996
Cl^-	Silty clay	1.00E-09	Spitz and Moreno, 1996
Cl^-	Silty clay	7.40E-10	Spitz and Moreno, 1996
Cl^-	Glaciolacustrine clay	5.80E-10	Spitz and Moreno, 1996
Cl^-	Varved glaciolacustrine	5.80E-10	Spitz and Moreno, 1996
Cl^-	Glaciomarine clay	2.00E-10	Spitz and Moreno, 1996
Br^-	Water	2.01E-09	Spitz and Moreno, 1996
HS^-	Water	1.73E-09	Spitz and Moreno, 1996
HCO_3^-	Water	1.18E-09	Spitz and Moreno, 1996
CO_3^{2-}	Water	9.55E-10	Spitz and Moreno, 1996
SO_4^{2-}	Water	1.07E-09	Spitz and Moreno, 1996
Dichloromethane	Fractured clay	1.24E-09	Ross and Lu, 1999
Tricholoroethylene	Fractured clay	1.01E-09	Ross and Lu, 1999
Uranium(VI)	Granite	3.00E-14	Yamaguchi *et al.*, 1997
NaCl	Sandstone (coarse)	6.33333E-11	IGS laboratory
NaCl	Sandstone (medium)	2.22778E-11	IGS laboratory
NaCl	Sandstone (medium)	1.89444E-11	IGS laboratory
NaCl	Sandstone (fine)	9.27778E-13	IGS laboratory
NaCl	Shale (coarse)	5.22222E-11	IGS laboratory
NaCl	Shale (medium)	4.94444E-11	IGS laboratory
NaCl	Shale (fine)	2.10833E-10	IGS laboratory
NaCl	Quartzite	5E-11	IGS laboratory
Na_2SO_4	Sandstone (coarse)	5.25E-11	IGS laboratory
Na_2SO_4	Sandstone (medium)	7.44444E-12	IGS laboratory
Na_2SO_4	Sandstone (medium)	6.69444E-12	IGS laboratory
Na_2SO_4	Sandstone (fine)	6.69444E-12	IGS laboratory
Na_2SO_4	Shale (coarse)	5.19444E-12	IGS laboratory
Na_2SO_4	Shale (medium)	6.08333E-12	IGS laboratory

B4. DISPERSIVITY VALUES *(Taken directly from Spitz and Moreno, 1996)*

Material	Migration Distance (m)	Dispersivity α_L (m)
Alluvium	15	3
Alluvium	40	3
Alluvium	15500	30.5
Alluvium, derived from tuff	91	20
Alluvium (gravels)	25	1
Alluvium (gravels)	290	41
Basalt, brecciated	17	0.60
Basalt, lava, and sediments	2000	91
Basalt, lava, and sediments	20000	910
Chalk	8	1.0
Chalk, fractured	8	3.1
Crystalline rock, fractured	538	134
Dolomite, fractured	21	2.1

Dolomite, fractured	23	5.2
Dolomite, fractured	55	38.1
Dolomite, fractured limestone	122	15
Dolomite	250	7
Granite, fractured	5	0.5
Granite, fractured	17	2
Gravel, fluvioglacial	10	5
Gravel with cobbles	54	1.4
Gravel	700	200
Limestone	91	11.6
Limestone	2000	170
Limestone, fractured	490	6.7
Limestone, fractured	32000	23
Sandstone	4	0.1
Sandstone and alluvial sediments	50000	200
Sandstone with silt and clay layers	28	1.0
Sand	3	0.03
Sand	5	0.1
Sand	6	0.18
Sand	8	0.5
Sand	13	1.0
Sand	100000	20000
Sand, glaciofluvial	11	0.08
Sand, glaciofluvial	90	0.5
Sand, glaciofluvial	600	45
Sand, glaciofluvial	700	7.6
Sand, glaciofluviatile	90	0.43
Sand, glaciofluviatile	600	45
Sand, fluvial	25	1.6
Sand, fine with glacial till	4	0.06
Sand, medium, to fine	57	1.5
Sand, medium to coarse	250	0.96
Sand, medium, layered	38	4.0
Sand and gravel	2	0.015
Sand and gravel	18	0.26
Sand and gravel	25	11
Sand and gravel	150	25
Sand and gravel	43400	91.4
Sand, gravel and silt	11	2
Sand, gravel and silt	43	11
Sand, silt and gravel	16	1
Sand, silt and gravel	79	15.2
Sand, silt and clay	57	0.76
Sand and gravel, very heterogeneous	200	7.5
Sand and gravel, glaciofluvial	3500	6
Sand and gravel, glaciofluvial	20000	30.5
Sand and gravel, glaciofluviatile	4000	460
Sand and gravel with cobbles	6	11
Sand and gravel with clay lenses, alluvial	800	15
Sand and gravel with clay lenses,	1000	12

alluvial		
Sand and gravel, layered and silty	10	0.7
Sand and gravel, layered and silty	100	8
Sand and gravel, layered and silty	500	58
Sand and gravel with clay lenses	19	2.5

B5. EQUATIONS USED TO DETERMINE CONTAMINANT CONCENTRATIONS IN THE COMPREHENSIVE CONTAMINATION RISK ASSESSMENT

(Taken directly from Fetter, 1999)

Continuous injection of a contaminant in a two-dimensional flow field:

$$C(x,y)=\frac{C_0(Q/b)}{2\pi(D_L D_T)^{1/2}}\exp\left(\frac{vx}{2D_L}\right)K_0\left[\left(\frac{v}{2D_L}\left(\frac{x^2}{D_L}+\frac{y^2}{D_T}\right)\right)^{1/2}\right]$$

where

C = Concentration at position (x,y)

C_0 = Initial concentration of contaminant

Q = Rate at which contaminant is being injected

b = Thickness of the aquifer over which the contaminant is being injected

D_L = Dispersion coefficient parallel to the principal flow direction

D_T = Dispersion coefficient perpendicular to the principal flow direction

K_0 = Modified Bessel function of the second kind and zero order

and

$$v=\frac{K}{n_e}\frac{dh}{dl}$$

where

K = Hydraulic conductivity

n_e = Effective porosity

$\frac{dh}{dl}$ = Hydraulic gradient

Slug injection of a contaminant in a two-dimensional flow field:

$$C(x,y,t)=\frac{C_0A}{4\pi t(D_L D_T)^{1/2}}\exp\left[-\frac{((x-x_0)-v_x t)^2}{4D_L t}-\frac{(y-y_0)^2}{4D_T t}\right]$$

where

$C(x,y,t)$ = Concentration at position (x,y) at time t

A = Area over which contaminant is being injected

(x_0,y_0) = Position at which contaminant is being injected

t = Time of slug injection

Mass transport equation used to calculate dispersivity values:

$$C = \frac{C_0}{2}\left[\operatorname{erfc}\left(\frac{L - vt}{2\sqrt{Dt}}\right)\right]$$

where $D = \alpha v$ and

α = Dispersivity

L = Distance between source and point at which concentration must be determined

t = Time of injection

B6. MEMBERSHIP FUNCTION RANGE FOR CONTAMINANT PROPERTIES

The membership function for the range of pollutant properties listed in Table 5.4 is dependent on diffusion (which includes matrix diffusion) and dispersion expressed in terms of dispersivity. The values are determined according to the following matrix:

		Longitudinal Dispersivity (m)				
		0 – 25	25 – 50	50 – 100	100 – 200	> 200
Diffusion (m^2/s)	$< 1E^{-11}$	Very high				
	$1E^{-10} - 1E^{-11}$		High			
	$1E^{-9} - 1E^{-10}$			Medium		
	$1E^{-8} - 1E^{-9}$				Low	
	$> 1E^{-8}$					Very low

B7. RANGE OF HYDRAULIC CONDUCTIVITY (K) VALUES *(Taken from Freeze and Cherry, 1979)*

Rock type	K (m/d) minimum	K (m/d) maximum
Gravel	10	1.00E+05
Sand	1.00E+00	1.00E+04
Silt	1.00E-03	10
Clay	1.00E-07	1.00E-02
Sandstone	1.00E-04	1.00E+01
Limestone, dolomite	1.00E-03	1.00E+03
Karst limestone	1.00E+00	1.00E+04
Shale	1.00E-07	1.00E-02
Basalt	1.00E-05	1.00E-01
Fractured basalt	1.00E-01	1.00E+04
Dense crystalline rock	1.00E-08	1.00E-04
Fractured crystalline rock	1.00E-02	1.00E+02

B8. RANGE OF POROSITY VALUES *(Taken from Freeze and Cherry, 1979)*

Formation	Porosity Range
Gravel	0.25 - 0.4
Sand	0.25 - 0.5
Silt	0.35 - 0.5
Clay	0.4 - 0.7
Fractured basalt	0.1 - 0.5
Karst limestone	0.1 - 0.5
Sandstone	0.05 - 0.3
Limestone, dolomite	0 - 0.2
Shale	0 - 0.1
Fractured crystalline rock	0 - 0.1
Dense crystalline rock	0 - 0.05
Other	
Gabbro weathered	0.43
Granite weathered	0.455
Granite	5.00E-03
Granite, fractured	0.05

APPENDIX C

Health Risk Assessment Information

C1. CARCINOGENIC CLASSIFICATION OF CONTAMINANTS *(Taken from Environmental Protection Agency, 2000)*

Contaminant	Carcinogenic rating
2,3,7,8,-TCDD (Dioxin)	B2
2,4,5,-TP (Silvex)	D
Acephate	C
Acrylamide	B2
Aldicarb	D
Aldrin & Dieldrin	B2
Aluminium	D
Ammonia	D
Antimony	D
Arsenic	A
Asbestos	A
Atrazine	C
Barium	D
Bentazon	E
Benzene	A
Benzo(a)Pyrene	B2
Beryllium	B1
Boron	D
Bromacil	C
Bromate	B2
Bromodichloromethane	B2
Bromoform	B2
Cadmium	D
Carbaryl	D
Carbofuran	E
Carbon Tetrachloride	B2
Chlordane	B2
Chlordimeform	D
Chlorfenvinphos	D
Chlorine	D
Chlorine dioxide	D
Chloroform	B2
Chlorphyrifos	D
Chromium III	D
Chromium VI	A
Cobalt	C
Copper	D
Cyanide	D
Cyhexatin	D
DDT	B
Diazinon	E
Dibromo-3-chloropropane 1,2-	B2
Dicamba	D
Dichloroacetic Acid	B2
Dichlorobenzene 1,2-	D
Dichlorobenzene 1,4-	C
Dichloroethane 1,1	C
Dichloroethane 1,2	B2
Dichloroethene 1,2-(Cis)	D
Dichloromethane	B2
Dichloropropene 1,3-	B2

Dichlorvos	B2
Dicofol	D
Dieldrin	B2
Dinoseb	D
Diquat	D
Disulfoton	E
Diuron	D
Endosulfan	D
Endrin	D
Ethylbenzene	D
Ethylene Dibromide (EDB)	B
Fluoride	D
Formaldehyde	B1
Glyphosate	D
Heptaclor	B2
Heptaclor Epoxide	B2
Hexachlorobenzene	B2
Hexachlorobutadiene	C
Hexachlorocyclopentadiene	D
Lead	B2
Lindane	C
Manganese	D
Mercury	D
Methidathion	C
Methoxychlor	D
Metolachlor	C
Metribuzin	D
Molydbenum	D
Monocrotophos	D
Nickel	C
Nitrate	-
Nitrate/Nitrite	-
Nitrite	-
PAH	D
Parathion	C
PCBs	C
Pentachlorophenol	B2
Phenols	D
Piperonyl Butoxide	C
Posphorus	D
Propoxur	B
Radon	A
Selenium	D
Silver	D
Styrene	C
Sulfate	-
Thallium	D
Thiram	D
Tin	D
Titanium	D
Toluene	D
Toxaphene	B2
Trichloroacetic Acid	C
Trichloroethane 1,1,1,-	D
Trichlorophenol 2,4,6-	B2
Trifluralin	C
Uranium	A
$Uranium^{238}$	A
Vinyl Chloride	A
Xylene	D
Zinc	D

C2. CANCER POTENCY FACTORS *(Taken from Environmental Protection Agency, 1998)*

Contaminant	Oral slope factor (mg/kg/d)
Aldrin & Dieldrin	1.70E+01
Arsenic	1.50E+00
Benzene	1.50E-02
Benzo(a)Pyrene	7.3
Bromoform	7.90E-03
Carbon Tetrachloride	1.30E-01
Chloroform	6.10E-03
Dichloropropene 1,3-	1.00E-01
Dieldrin	1.60E+01
Heptaclor	4
Heptaclor Epoxide	9.1
Hexachlorobenzene	1.6
Hexachlorobutadiene	7.80E-02
Pentachlorophenol	1.20E-01
Toxaphene	1.1
Trichlorophenol 2,4,6-	1.10E-02
Vinyl Chloride	1.4

C3. REFERENCE DOSES *(Taken from Environmental Protection Agency, 1998)*

Contaminant	Oral RfD (mg/kg/d)	Inhalation RfC (mg/kg/d)
2,3,7,8,-TCDD (Dioxin)	1.00E-09	
2,4,5,-TP (Silvex)	0.008	
Aldicarb	0.001	
Aldrin & Dieldrin	0.00003	
Antimony	0.0004	
Atrazine	0.035	
Bentazon	0.03	
Beryllium	0.002	2.00E-02
Boron	0.09	
Bromacil	0.1	
Bromodichloromethane	0.02	
Bromoform	0.02	
Cadmium	0.0005	
Carbaryl	0.1	
Carbofuran	0.005	
Carbon Tetrachloride	0.0007	
Chlordane	0.0005	
Chlorine	0.1	
Chlorine dioxide	0.03	
Chloroform	0.01	
Chlorphyrifos	0.003	
Chromium III	0.003	
Chromium VI	0.003	
Cyanide	0.02	
Diazinon	0.00009	
Dicamba	0.03	
Dichloroacetic Acid	0.004	
Dichlorobenzene 1,2-	0.09	
Dichlorobenzene 1,4-	0.09	0.8
Dichloroethane 1,2	9.10E-02	
Dichloromethane	0.06	
Dichloropropene 1,3-	0.03	2.00E-02
Dieldrin	0.00005	
Dinoseb	0.001	
Diquat	0.002	

Disulfoton	0.00004	
Diuron	0.002	
Endrin	0.0003	
Ethylbenzene	0.1	1
Fluoride	0.06	
Formaldehyde	0.15	
Glyphosate	0.1	
Heptaclor	0.0005	
Heptaclor Epoxide	0.00001	
Hexachlorobenzene	0.0008	
Hexachlorobutadiene	0.002	
Hexachlorocyclopentadiene	0.007	
Lindane	0.0003	
Manganese	0.14	
Mercury	0.0003	
Methoxychlor	0.005	
Metolachlor	0.15	
Metribuzin	0.025	
Molydbenum	0.005	
Nickel	0.02	
Nitrate	1.6	
Nitrite	0.16	
Pentachlorophenol	0.03	
Phenols	0.6	
Posphorus	0.00002	
Selenium	0.005	
Silver	0.005	
Styrene	0.2	
Thallium	0.00007	
Toluene	0.2	0.4
Toxaphene	0.0004	
Trichloroacetic Acid	0.1	
Trichloroethane 1,1,1,-	0.035	
Trichlorophenol 2,4,6-	0.0003	
Trifluralin	0.0075	
Uranium	0.003	
$Uranium^{238}$	0.003	
Vinyl Chloride	0.003	1.00E-01
Xylene	2	
Zinc	0.3	

C4. CLASSIFICATION OF MICROBIOLOGICAL AGENTS FOR RAPID ASSESSMENT *(Taken from Quality of Domestic Water Supplies, 2001 and Canadian Material Safety Data Sheets, 2001)*

Infectious agent	Rating
Aerococcus spp.	Effects common
Aeromonas hydrophila	Effects common
Ancylostoma duodenale	Long-term effects
Ascaris lumbricoides	Effects common
Ascaris spp.	Death
Balantidium coli	Effects common
Burkholderia (Pseudomonas) pseudomallei	Death
Campylobacter	Effects common
Citrobacter spp.	Death
Clostridium difficile	Death
Clostridium perfringens	Effects common
Clostridium tetani	Death
Clostridium spp.	Effects common
Coxsackievirus	Long-term effects
Cryptosporidium parvum	Effects common

Echinococcus granulosus	Long-term effects
Echovirus	Death
Edwardsiella tarda	Effects common
Entamoeba coli	Death
Entamoeba histolytica	Death
Enterobacter spp.	Effects common
Escherichia coli, enterohemorrhagic	Death
Escherichia coli, enteroinvasive	Effects common
Escherichia coli, enteropathogenic	Effects common
Escherichia coli, enterotoxigenic	Effects common
Fasciola hepatica, Fasciola gigantica	Effects common
Faecal coliforms	Effects common
Giardia lamblia	Effects common
Hepatitis A virus	Death
Hepatitis E virus	Death
Human rotavirus	Death
Klebsiella spp.	Effects common
Leptospira interrogans	Death
Micrococcus spp.	Few effects
Naegleria fowleri	Death
Norwalk virus	Death
Plesiomonas shigelloides	Effects common
Proteus spp.	Effects common
Pseudomonas spp.	Death
Rotavirus	Death
Salmonella choleraesuis	Death
Salmonella spp.	Effects common
Salmonella typhi	Death
Schistosoma spp.	Effects common
Serratia spp.	Death
Shigella dysenteriae	Effects common
Shigella spp.	Death
Streptobacillus moniliformis	Effects common
Taenia solium	Effects common
Total coliforms	Effects common
Vibrio cholerae, serogroup O1, serogoup O139	Death
Yersinia enterocolitica, Yersinia pseudotuberculosis	Death

C5. PARAMETERS FOR MICROBIOLOGICAL ASSESSMENT *(Taken from Rose and Gerba, 1991)*

Micro-organism	α	β	r
Campylobacter	0.039	55	-
Salmonella	0.33	139.9	-
Salmonella typhi	0.21	5531	-
Shigella	0.16	155	-
Shigella dysenteriae	0.5	100	-
Shigella flexneri 2A##	0.2	2000	-
Vibrio cholera classical	0.097	13020	-
Vibrio clolera El Tor	$2.7x10^{-5}$	1.33	-
Poliovirus 1	15	1000	-
Poliovirus 3	0.5	1.14	-
Echovirus 12	1.3	75	-
Rotavirus	0.232	0.247	-
Entamoeba coli	0.17	1.32	-
Entamoeba histolytica	13.3	39.7	-
Giardia lamblia	-	-	0.0199
Cryptosporidium parvum	-	-	0.00419

C6. REVISED RADIOGENIC RISK COEFFICIENTS *(Taken directly from Environmental Protection Agency, 1994)*

Mortality Risk Coefficients

Nuclide	Ingestion (Bq^{-1})	Inhalation (Bq^{-1})	Submersion (per Bq y/m^3)
H-3	1.28E-12	1.73E-12	
Be-7	1.38E-12	3.56E-12	2.83E-9
C-11	1.01E-12	8.36E-13	5.83E-8
C-14	1.93E-11	1.31E-13	
C-15	1.58E-14	2.06E-14	2.68E-7
N-13	7.01E-13	6.36E-13	5.83E-8
O-15	2.23E-13	2.45E-13	5.83E-8
F-18	2.34E-12	1.56E-12	5.65E-8
Na-22	1.50E-10	8.95E-11	1.29E-7
Na-24	2.57E-11	1.52E-11	2.82E-7
Si-31	8.42E-12	8.09E-12	5.35E-11
P-32	1.14E-10	6.21E-11	
P-33	1.42E-11	7.91E-12	
S-35	6.92E-12	3.33E-12	
Cl-36	4.02E-11	2.36E-11	3.27E-16
Cl-38	4.72E-12	4.06E-12	1.01E-7
Ar-41	1.05E-14	7.74E-8	1.35E-9
K-40	2.28E-10	1.33E-10	9.49E-9
K-42	2.36E-11	1.65E-11	1.70E-8
Ca-45	3.84E-11	5.77E-11	5.92E-19
Ca-47	1.05E-10	1.04E-10	6.41E-8
Sc-46	8.87E-11	2.73E-10	1.22E-7
Sc-47	4.44E-11	3.83E-11	6.10E-9
Sc-48	1.03E-10	7.99E-11	2.04E-7
V-48	1.17E-10	1.32E-10	1.76E-7
Cr-51	2.16E-12	3.59E-12	1.77E-9
Mn-52	9.59E-11	8.34E-11	2.08E-7
Mn-54	3.32E-11	7.31E-11	5.05E-8
Mn-56	1.46E-11	1.26E-11	1.09E-7
Fe-55	6.24E-12	1.08E-11	8.87E-13
Fe-59	9.56E-11	1.37E-10	7.20E-8
Co-57	1.65E-11	6.47E-11	6.65E-9
Co-58	4.69E-11	1.07E-10	5.83E-8
Co-58m	1.49E-12	1.93E-12	1.33E-12
Co-60	3.36E-10	1.46E-9	1.51E-7
Ni-59	3.04E-12	8.00E-12	1.48E-12
Ni-63	8.85E-12	2.01E-11	
Ni-65	9.51E-12	8.80E-12	3.34E-8
Cu-64	8.29E-12	9.33E-12	1.09E-8
Zn-65	1.78E-10	1.94E-10	3.52E-8
Zn-69	1.29E-12	2.67E-12	3.40E-13
Zn-69m	2.36E-11	2.57E-11	2.36E-8
Ga-67	1.28E-11	9.81E-12	7.97E-9
Ga-72	7.38E-11	4.39E-11	1.77E-7
Ge-71	2.03E-13	1.45E-12	3.52E-12
As-73	1.28E-11	3.09E-11	1.97E-10
As-74	6.62E-11	9.71E-11	4.43E-8
As-76	1.01E-10	9.16E-11	2.55E-8
As-77	2.52E-11	2.40E-11	4.86E-10
Se-75	1.21E-10	9.46E-11	2.17E-8
Br-82	2.54E-11	1.45E-11	1.58E-7
Kr-83m		7.81E-16	3.41E-12
Kr-85		6.08E-15	1.28E-10
Kr-85m		5.93E-15	8.83E-9

Kr-87		2.68E-14	5.23E-8
Kr-88		4.60E-14	1.34E-7
Kr-89		3.68E-14	1.19E-7
Kr-90		3.86E-14	7.82E-8
Rb-82	2.51E-13	3.00E-13	6.29E-8
Rb-86	1.38E-10	8.28E-11	5.75E-9
Rb-87	7.27E-11	4.43E-11	
Rb-88	3.47E-12	3.46E-12	4.22E-8
Rb-89	1.97E-12	1.73E-12	1.33E-7
Sr-82	4.06E-10	1.68E-10	1.20E-11
Sr-85	2.39E-11	2.07E-11	2.92E-8
Sr-85m	3.38E-13	1.51E-13	1.21E-8
Sr-89	1.63E-10	7.18E-11	8.32E-12
Sr-90	9.64E-10	1.51E-9	
Sr-91	4.42E-11	1.46E-11	4.16E-8
Sr-92	3.14E-11	8.53E-12	8.09E-8
Y-90	2.25E-10	1.89E-10	
Y-91	2.02E-10	4.05E-10	2.18E-10
Y-91m	6.76E-13	7.02E-13	3.06E-8
Y-92	3.15E-11	3.92E-11	1.53E-8
Y-93	8.76E-11	7.55E-11	5.60E-9
Zr-93	8.55E-12	1.29E-10	
Zr-95	5.99E-11	1.33E-10	4.39E-8
Zr-97	1.57E-10	9.39E-11	1.09E-8
Nb-93m	1.00E-11	1.07E-10	4.42E-12
Nb-94	1.08E-10	1.79E-9	9.47E-8
Nb-95	3.50E-11	6.27E-11	4.59E-8
Nb-95m	4.60E-11	4.32E-11	3.34E-9
Nb-97	3.34E-12	5.38E-12	3.92E-8
Nb-97m	6.41E-14	8.41E-14	4.36E-8
Mo-99	3.88E-11	8.60E-11	9.15E-9
Tc-95	1.22E-12	7.59E-13	4.72E-8
Tc-95m	2.22E-11	4.38E-11	3.91E-8
Tc-96	3.95E-11	3.86E-11	1.51E-7
Tc-96m	4.66E-13	4.83E-13	2.50E-9
Tc-97	2.83E-12	8.02E-12	3.05E-11
Tc-97m	2.10E-11	4.49E-11	4.33E-11
Tc-99	2.49E-11	6.75E-11	2.63E-14
Tc-99m	8.87E-13	7.66E-13	7.02E-9
Ru-97	9.18E-12	7.83E-12	1.28E-8
Ru-103	5.09E-11	9.66E-11	2.76E-8
Ru-105	1.83E-11	1.82E-11	4.62E-8
Ru-106	5.28E-10	2.75E-9	
Rh-103m	1.66E-13	3.26E-13	6.59E-12
Rh-105	2.91E-11	2.38E-11	4.37E-9
Rh-105m	1.98E-14	2.11E-14	1.51E-9
Rh-106	8.78E-14	1.18E-13	1.21E-8
Pd-100	5.76E-11	6.71E-11	
Pd-101	5.89E-12	4.82E-12	
Pd-103	1.58E-11	2.23E-11	6.03E-11
Pd-107	3.14E-12	3.61E-11	
Pd-109	5.05E-11	4.17E-11	3.94E-11
Ag-105	2.67E-11	4.75E-11	
Ag-108	1.69E-13	2.42E-13	1.02E-9
Ag-108m	1.03E-10	1.49E-9	9.41E-8
Ag-109m	6.55E-15	8.87E-15	2.04E-10
Ag-110	5.94E-14	8.10E-14	1.80E-9
Ag-110m	1.43E-10	6.78E-10	1.65E-7
Ag-111	1.03E-10	1.01E-10	1.48E-9
Cd-109	1.38E-10	4.29E-10	7.25E-11
Cd-115	1.10E-10	9.45E-11	1.17E-8
Cd-115m	2.19E-10	3.64E-10	1.33E-9
In-113m	1.50E-12	1.43E-12	1.44E-8
In-114	1.10E-13	1.49E-13	1.85E-9

In-114m	3.18E-10	5.39E-10	5.15E-9
In-115	8.14E-10	5.00E-9	
In-115m	5.46E-12	4.09E-12	8.92E-9
Sn-113	5.66E-11	1.46E-10	3.92E-10
Sn-121	1.84E-11	1.20E-11	
Sn-121m	3.08E-11	1.63E-10	1.23E-11
Sn-125	2.51E-10	2.32E-10	1.88E-8
Sn-126	3.26E-10	9.07E-10	2.36E-9
Sb-122	1.33E-10	1.04E-10	2.57E-8
Sb-124	1.65E-10	2.70E-10	1.16E-7
Sb-125	4.59E-11	1.10E-10	2.43E-8
Sb-126	1.51E-10	1.62E-10	1.63E-7
Sb-126m	1.60E-12	1.62E-12	9.22E-8
Sb-127	1.28E-10	1.16E-10	3.88E-8
Sb-129	2.92E-11	1.95E-11	8.69E-8
Te-125m	4.08E-11	6.14E-11	3.42E-10
Te-127	1.32E-11	9.46E-12	2.74E-10
Te-127m	1.02E-10	2.99E-10	1.12E-10
Te-129	2.90E-12	3.71E-12	3.08E-9
Te-129m	1.84E-10	2.87E-10	1.94E-9
Te-131	2.59E-12	2.67E-12	2.44E-8
Te-131m	8.77E-11	7.06E-11	8.59E-8
Te-132	1.66E-10	1.45E-10	1.19E-8
I-122	5.12E-13	5.69E-13	5.59E-8
I-123	2.24E-12	1.31E-12	8.58E-9
I-125	7.24E-11	4.78E-11	3.86E-10
I-126	1.38E-10	9.01E-11	2.65E-8
I-129	5.06E-10	3.35E-10	2.98E-10
I-130	2.04E-11	1.19E-11	1.26E-7
I-131	1.04E-10	6.72E-11	2.16E-8
I-132	6.30E-12	4.00E-12	1.37E-7
I-133	3.53E-11	2.11E-11	3.52E-8
I-134	3.87E-12	2.62E-12	1.60E-7
I-135	1.12E-11	6.80E-12	9.74E-8
Xe-122		5.60E-14	3.23E-9
Xe-123		1.39E-14	3.63E-8
Xe-125		1.93E-14	1.38E-8
Xe-127		7.37E-15	1.44E-8
Xe-129m		1.09E-14	1.01E-9
Xe-131m		7.86E-15	3.65E-10
Xe-133		7.87E-15	1.64E-9
Xe-133m		9.81E-15	1.54E-9
Xe-135		1.44E-14	1.39E-8
Xe-135m		3.81E-15	2.45E-8
Xe-137		3.17E-14	1.10E-8
Xe-138		4.21E-14	7.33E-8
Cs-131	3.28E-12	1.91E-12	2.51E-10
Cs-134	8.49E-10	5.01E-10	9.22E-8
Cs-134m	9.17E-13	7.09E-13	1.04E-9
Cs-135	8.27E-11	4.78E-11	
Cs-136	1.38E-10	8.10E-11	1.30E-7
Cs-137	5.71E-10	3.34E-10	
Cs-138	3.96E-12	3.21E-12	1.49E-7
Ba-131	2.64E-11	8.35E-12	2.56E-8
Ba-133	4.53E-11	7.90E-11	2.02E-8
Ba-133m	4.17E-11	9.49E-12	3.03E-9
Ba-137m	5.35E-14	3.90E-14	3.52E-8
Ba-139	5.72E-12	3.59E-12	1.96E-9
Ba-140	1.78E-10	5.49E-11	1.07E-8
La-140	1.44E-10	9.75E-11	1.44E-7
Ce-141	5.86E-11	8.99E-11	4.07E-9
Ce-143	8.91E-11	7.48E-11	1.46E-8
Ce-144	4.42E-10	2.60E-9	9.32E-10
Pr-142	1.05E-10	8.44E-11	3.64E-9

Pr-143	9.88E-11	1.10E-10	5.33E-16
Pr-144	1.91E-12	3.37E-12	2.10E-9
Pr-144m	7.46E-13	1.44E-12	2.01E-10
Nd-147	8.82E-11	9.47E-11	7.23E-9
Nd-149	7.60E-12	9.89E-12	2.12E-8
Pm-147	2.12E-11	1.84E-10	1.91E-13
Pm-148	2.17E-10	2.00E-10	3.46E-8
Pm-148m	1.52E-10	6.26E-10	1.17E-7
Pm-149	8.27E-11	6.83E-11	6.59E-10
Sm-147	5.12E-10	1.69E-7	
Sm-151	6.99E-12	1.15E-10	3.02E-14
Sm-153	6.04E-11	4.17E-11	2.45E-9
Eu-152	9.17E-11	1.69E-9	6.79E-8
Eu-154	1.47E-10	2.01E-9	7.51E-8
Eu-155	2.54E-11	2.23E-10	2.81E-9
Eu-156	1.65E-10	1.83E-10	8.59E-8
Gd-153	2.01E-11	7.03E-11	4.18E-9
Gd-159	3.93E-11	2.48E-11	2.04E-9
Tb-158	6.54E-11	1.53E-9	4.55E-8
Tb-160	1.16E-10	2.37E-10	6.48E-8
Dy-165	5.54E-12	5.54E-12	1.34E-9
Dy-166	1.40E-10	1.49E-10	1.48E-9
Ho-166	1.14E-10	7.92E-11	1.54E-9
Er-169	3.17E-11	2.93E-11	9.54E-14
Er-171	2.53E-11	1.65E-11	2.03E-8
Tm-170	1.12E-10	2.41E-10	2.18E-10
Tm-171	8.79E-12	4.23E-11	2.33E-11
Yb-169	5.21E-11	8.31E-11	1.45E-8
Yb-175	3.60E-11	3.19E-11	2.18E-9
Lu-177	4.42E-11	4.22E-11	1.87E-9
Hf-181	8.30E-11	1.26E-10	3.05E-8
Ta-182	1.07E-10	3.61E-10	7.70E-8
W-181	4.29E-12	1.47E-12	1.47E-9
W-185	3.07E-11	7.29E-12	1.46E-12
W-187	3.77E-11	9.25E-12	2.74E-8
Re-183	2.82E-11	5.77E-11	7.12E-9
Re-186	4.80E-11	5.47E-11	1.04E-9
Re-187	1.63E-13	4.41E-13	
Re-188	4.69E-11	4.89E-11	3.31E-9
Os-185	2.86E-11	9.57E-11	4.08E-8
Os-191	4.58E-11	5.38E-11	3.44E-9
Os-191m	7.50E-12	6.88E-12	1.89E-10
Os-193	6.56E-11	5.26E-11	3.65E-9
Ir-190	7.68E-11	8.70E-11	7.98E-8
Ir-192	9.84E-11	2.42E-10	4.64E-8
Ir-194	1.06E-10	8.49E-11	5.28E-9
Pt-191	2.30E-11	7.09E-12	1.51E-8
Pt-193	2.43E-12	1.38E-12	1.70E-12
Pt-193m	3.76E-11	9.62E-12	4.56E-10
Pt-197	3.21E-11	7.82E-12	1.14E-9
Pt-197m	5.32E-12	2.07E-12	4.06E-9
Au-196	2.04E-11	2.00E-11	2.60E-8
Au-198	7.99E-11	7.02E-11	2.29E-8
Hg-197	1.79E-11	1.33E-11	2.99E-9
Hg-203	4.02E-11	6.10E-11	1.27E-8
Tl-202	1.83E-11	1.08E-11	2.58E-8
Tl-204	3.54E-11	2.10E-11	4.84E-11
Tl-207	2.61E-13	3.16E-13	1.32E-10
Tl-208	3.95E-13	3.42E-13	2.33E-7
Tl-209	3.08E-13	2.82E-13	1.28E-7
Pb-203	1.62E-11	5.66E-12	1.62E-8
Pb-209	3.45E-12	1.45E-12	
Pb-210	1.46E-8	3.59E-8	5.49E-11
Pb-211	7.15E-12	2.61E-10	3.00E-9

Pb-212	2.99E-10	8.68E-10	7.98E-9
Pb-214	6.02E-12	1.56E-10	1.39E-8
Bi-206	1.11E-10	9.61E-11	1.98E-7
Bi-207	7.82E-11	1.95E-10	9.16E-8
Bi-210	1.10E-10	1.28E-9	
Bi-211	4.42E-13	4.48E-11	2.66E-9
Bi-212	1.22E-11	9.35E-10	1.11E-8
Bi-213	8.90E-12	7.92E-10	7.90E-9
Bi-214	4.45E-12	3.74E-10	9.48E-8
Po-210	5.88E-9	5.14E-8	5.13E-13
Po-212	1.10E-21	1.52E-19	
Po-213	1.57E-20	2.00E-18	1.83E-12
Po-214	5.16E-19	7.12E-17	5.02E-12
Po-215	1.13E-17	1.15E-15	8.46E-12
Po-216	1.59E-15	7.56E-14	8.75E-13
Po-218	1.10E-12	9.44E-11	
At-217	1.98E-16	1.32E-14	1.39E-11
Rn-219		1.74E-12	3.22E-9
Rn-220		4.42E-12	3.01E-11
Rn-222		3.21E-11	2.22E-11
Fr-221	3.04E-12	2.05E-10	1.70E-9
Fr-223	7.91E-12	1.17E-11	2.34E-9
Ra-223	3.91E-9	9.12E-8	7.18E-9
Ra-224	2.46E-9	5.70E-8	5.57E-10
Ra-225	2.88E-9	6.01E-8	2.63E-10
Ra-226	5.26E-9	6.62E-8	3.71E-10
Ra-228	4.48E-9	2.22E-8	2.48E-18
Ac-225	2.19E-9	1.06E-7	7.03E-10
Ac-227	8.17E-9	1.78E-6	6.41E-12
Ac-228	2.55E-11	8.33E-10	5.58E-8
Th-227	6.11E-10	1.10E-7	5.72E-9
Th-228	9.84E-10	2.41E-6	1.01E-10
Th-229	9.94E-10	1.91E-6	4.42E-9
Th-230	6.39E-10	4.22E-7	1.88E-11
Th-231	2.70E-11	2.18E-11	5.60E-10
Th-232	5.61E-10	4.73E-7	8.51E-12
Th-234	2.88E-10	3.89E-10	3.78E-10
Pa-231	2.86E-9	5.85E-7	1.65E-9
Pa-233	7.05E-11	1.01E-10	1.17E-8
Pa-234	3.37E-11	2.91E-11	1.17E-7
Pa-234m	1.16E-13	1.61E-13	6.90E-10
U-232	1.40E-9	1.35E-6	1.23E-11
U-233	7.44E-10	3.63E-7	1.21E-11
U-234	7.38E-10	3.58E-7	6.72E-12
U-235	7.53E-10	3.33E-7	8.29E-9
U-236	6.99E-10	3.39E-7	5.12E-12
U-237	6.01E-11	5.99E-11	6.96E-9
U-238	7.31E-10	3.19E-7	4.36E-12
U-240	8.29E-11	6.98E-11	2.79E-11
Np-236	1.43E-11	8.96E-11	6.80E-9
Np-237	6.65E-9	8.04E-7	1.13E-9
Np-238	6.92E-11	9.80E-11	3.36E-8
Np-239	6.42E-11	4.61E-11	8.96E-9
Np-240	3.42E-12	3.26E-12	6.81E-8
Np-240m	5.76E-13	7.24E-13	1.94E-8
Pu-236	1.56E-9	3.39E-7	4.66E-12
Pu-238	6.64E-9	6.76E-7	3.32E-12
Pu-239	7.12E-9	6.82E-7	3.83E-12
Pu-240	7.11E-9	6.81E-7	3.26E-12
Pu-241	1.19E-10	6.55E-9	
Pu-242	6.76E-9	6.47E-7	2.78E-12
Pu-243	5.80E-12	6.29E-12	1.16E-9
Pu-244	6.95E-9	6.53E-7	1.94E-12
Am-241	7.39E-9	8.96E-7	8.46E-10

Am-242	2.25E-11	2.52E-10	7.03E-10
Am-242m	6.74E-9	8.08E-7	2.01E-11
Am-243	7.36E-9	8.89E-7	2.43E-9
Cm-242	6.60E-10	7.81E-8	3.62E-12
Cm-243	5.58E-9	6.75E-7	6.82E-9
Cm-244	4.66E-9	5.70E-7	3.04E-12
Cm-245	7.54E-9	9.12E-7	3.69E-9
Cm-246	7.48E-9	9.08E-7	2.49E-12
Cm-247	6.93E-9	8.34E-7	1.79E-8
Cm-248	2.90E-8	3.39E-6	2.26E-12
Cf-252	3.50E-9	6.59E-7	2.79E-12

Morbidity Risk Coefficients

Nuclide	Ingestion (Bq^{-1})	Inhalation (Bq^{-1})	Submersion (per Bq y/m^3)
H-3	1.93E-12	2.59E-12	
Be-7	2.33E-12	4.81E-12	4.31E-9
C-11	1.21E-12	9.14E-13	8.87E-8
C-14	2.79E-11	1.89E-13	
C-15	1.79E-14	2.18E-14	4.05E-7
N-13	8.25E-13	6.84E-13	8.87E-8
O-15	2.57E-13	2.60E-13	8.87E-8
F-18	2.94E-12	1.77E-12	8.59E-8
Na-22	2.17E-10	1.32E-10	1.96E-7
Na-24	3.74E-11	2.03E-11	4.28E-7
Si-31	1.36E-11	8.90E-12	8.13E-11
P-32	1.65E-10	7.92E-11	
P-33	2.11E-11	1.07E-11	
S-35	1.12E-11	5.01E-12	
Cl-36	6.04E-11	3.51E-11	6.32E-16
Cl-38	5.58E-12	4.41E-12	1.54E-7
Ar-41		1.27E-14	1.17E-7
K-40	3.39E-10	2.02E-10	1.44E-8
K-42	3.48E-11	2.04E-11	2.57E-8
Ca-45	5.46E-11	6.79E-11	1.13E-18
Ca-47	1.80E-10	1.41E-10	9.74E-8
Sc-46	1.55E-10	3.53E-10	1.85E-7
Sc-47	7.97E-11	5.44E-11	9.42E-9
Sc-48	1.80E-10	1.13E-10	3.10E-7
V-48	2.04E-10	1.85E-10	2.67E-7
Cr-51	3.74E-12	4.70E-12	2.71E-9
Mn-52	1.62E-10	1.19E-10	3.16E-7
Mn-54	5.30E-11	9.98E-11	7.68E-8
Mn-56	2.32E-11	1.41E-11	1.65E-7
Fe-55	9.50E-12	1.51E-11	1.71E-12
Fe-59	1.59E-10	1.91E-10	1.09E-7
Co-57	2.62E-11	7.78E-11	1.03E-8
Co-58	7.62E-11	1.40E-10	8.85E-8
Co-58m	2.56E-12	2.41E-12	2.55E-12
Co-60	5.11E-10	1.86E-9	2.30E-7
Ni-59	5.00E-12	1.08E-11	2.85E-12
Ni-63	1.49E-11	2.74E-11	
Ni-65	1.52E-11	9.71E-12	5.07E-8
Cu-64	1.42E-11	1.13E-11	1.65E-8
Zn-65	2.68E-10	2.70E-10	5.34E-8
Zn-69	1.67E-12	2.82E-12	5.18E-13
Zn-69m	4.11E-11	3.16E-11	3.59E-8
Ga-67	2.26E-11	1.39E-11	1.23E-8
Ga-72	1.29E-10	5.87E-11	2.69E-7
Ge-71	3.19E-13	1.58E-12	6.79E-12
As-73	2.22E-11	3.69E-11	3.21E-10
As-74	1.14E-10	1.25E-10	6.74E-8

As-76	1.77E-10	1.17E-10	3.87E-8
As-77	4.46E-11	3.10E-11	7.43E-10
Se-75	1.77E-10	1.33E-10	3.33E-8
Br-82	3.83E-11	2.12E-11	2.41E-7
Kr-83m		9.40E-16	6.48E-12
Kr-85		7.75E-15	1.94E-10
Kr-85m		7.42E-15	1.36E-8
Kr-87		3.26E-14	7.93E-8
Kr-88		5.96E-14	2.03E-7
Kr-89		4.34E-14	1.81E-7
Kr-90		4.33E-14	1.19E-7
Rb-82	2.84E-13	3.17E-13	9.56E-8
Rb-86	1.92E-10	1.14E-10	8.74E-9
Rb-87	9.96E-11	6.12E-11	
Rb-88	3.96E-12	3.69E-12	6.39E-8
Rb-89	2.34E-12	1.87E-12	2.02E-7
Sr-82	6.97E-10	2.40E-10	2.29E-11
Sr-85	3.78E-11	3.08E-11	4.44E-8
Sr-85m	4.87E-13	1.93E-13	1.85E-8
Sr-89	2.79E-10	9.94E-11	1.26E-11
Sr-90	1.10E-9	1.61E-9	
Sr-91	7.62E-11	2.11E-11	6.32E-8
Sr-92	5.48E-11	1.27E-11	1.23E-7
Y-90	4.05E-10	2.68E-10	
Y-91	3.64E-10	5.01E-10	3.32E-10
Y-91m	9.98E-13	8.09E-13	4.65E-8
Y-92	5.26E-11	4.36E-11	2.32E-8
Y-93	1.55E-10	9.40E-11	8.51E-9
Zr-93	1.41E-11	1.42E-10	
Zr-95	1.06E-10	1.75E-10	6.68E-8
Zr-97	2.80E-10	1.28E-10	1.65E-8
Nb-93m	1.79E-11	1.17E-10	8.30E-12
Nb-94	1.87E-10	2.22E-9	1.44E-7
Nb-95	6.09E-11	8.40E-11	6.97E-8
Nb-95m	8.27E-11	6.08E-11	5.12E-9
Nb-97	4.74E-12	5.75E-12	5.96E-8
Nb-97m	8.85E-14	9.03E-14	6.62E-8
Mo-99	6.13E-11	1.21E-10	1.39E-8
Tc-95	1.84E-12	9.13E-13	7.17E-8
Tc-95m	3.36E-11	5.67E-11	5.95E-8
Tc-96	6.17E-11	5.25E-11	2.29E-7
Tc-96m	7.05E-13	6.11E-13	3.81E-9
Tc-97	4.27E-12	9.31E-12	5.69E-11
Tc-97m	3.24E-11	5.30E-11	7.56E-11
Tc-99	3.79E-11	7.81E-11	4.14E-14
Tc-99m	1.51E-12	9.43E-13	1.09E-8
Ru-97	1.59E-11	1.10E-11	1.96E-8
Ru-103	8.98E-11	1.24E-10	4.20E-8
Ru-105	3.12E-11	2.17E-11	7.02E-8
Ru-106	9.32E-10	3.11E-9	
Rh-103m	2.21E-13	3.45E-13	1.20E-11
Rh-105	5.22E-11	3.30E-11	6.66E-9
Rh-105m	2.92E-14	2.50E-14	2.34E-9
Rh-106	9.80E-14	1.25E-13	1.84E-8
Pd-100	1.01E-10	9.60E-11	
Pd-101	1.01E-11	6.18E-12	
Pd-103	2.85E-11	2.92E-11	1.09E-10
Pd-107	5.66E-12	3.94E-11	
Pd-109	9.00E-11	5.37E-11	5.98E-11
Ag-105	4.41E-11	6.28E-11	
Ag-108	1.88E-13	2.55E-13	1.55E-9
Ag-108m	1.64E-10	1.90E-9	1.43E-7
Ag-109m	7.32E-15	9.34E-15	3.31E-10
Ag-110	6.60E-14	8.53E-14	2.74E-9

Ag-110m	2.28E-10	8.69E-10	2.50E-7
Ag-111	1.85E-10	1.42E-10	2.26E-9
Cd-109	2.16E-10	5.00E-10	1.31E-10
Cd-115	1.97E-10	1.33E-10	1.77E-8
Cd-115m	3.84E-10	4.60E-10	2.02E-9
In-113m	2.24E-12	1.56E-12	2.20E-8
In-114	1.23E-13	1.57E-13	2.81E-9
In-114m	5.56E-10	6.83E-10	7.87E-9
In-115	9.43E-10	5.60E-9	
In-115m	9.24E-12	4.74E-12	1.36E-8
Sn-113	1.01E-10	1.79E-10	6.29E-10
Sn-121	3.31E-11	1.66E-11	
Sn-121m	5.40E-11	2.02E-10	2.08E-11
Sn-125	4.53E-10	3.23E-10	2.85E-8
Sn-126	5.73E-10	1.15E-9	3.74E-9
Sb-122	2.38E-10	1.47E-10	3.91E-8
Sb-124	2.91E-10	3.57E-10	1.76E-7
Sb-125	8.02E-11	1.41E-10	3.69E-8
Sb-126	2.63E-10	2.27E-10	2.47E-7
Sb-126m	1.97E-12	1.74E-12	1.40E-7
Sb-127	2.29E-10	1.63E-10	5.89E-8
Sb-129	5.02E-11	2.32E-11	1.32E-7
Te-125m	6.78E-11	7.70E-11	5.94E-10
Te-127	2.31E-11	1.17E-11	4.17E-10
Te-127m	1.62E-10	3.53E-10	1.94E-10
Te-129	4.00E-12	3.96E-12	4.70E-9
Te-129m	3.18E-10	3.60E-10	2.97E-9
Te-131	1.05E-11	6.71E-12	3.72E-8
Te-131m	2.38E-10	2.27E-10	1.31E-7
Te-132	3.29E-10	2.26E-10	1.83E-8
I-122	5.84E-13	6.05E-13	8.49E-8
I-123	1.47E-11	7.94E-12	1.33E-8
I-125	6.98E-10	4.62E-10	6.63E-10
I-126	1.30E-9	8.52E-10	3.97E-8
I-129	4.98E-9	3.30E-9	5.03E-10
I-130	1.31E-10	7.06E-11	1.91E-7
I-131	9.77E-10	6.31E-10	3.24E-8
I-132	1.79E-11	9.51E-12	2.09E-7
I-133	2.86E-10	1.63E-10	5.35E-8
I-134	6.25E-12	3.74E-12	2.43E-7
I-135	6.14E-11	3.19E-11	1.48E-7
Xe-122		8.34E-14	4.99E-9
Xe-123		2.41E-14	5.53E-8
Xe-125		3.25E-14	2.12E-8
Xe-127		1.10E-14	2.22E-8
Xe-129m		1.55E-14	1.65E-9
Xe-131m		1.12E-14	5.99E-10
Xe-133		1.12E-14	2.62E-9
Xe-133m		1.38E-14	2.39E-9
Xe-135		2.01E-14	2.12E-8
Xe-135m		5.09E-15	3.72E-8
Xe-137		3.76E-14	1.67E-8
Xe-138		5.58E-14	1.11E-7
Cs-131	4.87E-12	2.87E-12	4.35E-10
Cs-134	1.28E-9	7.80E-10	1.40E-7
Cs-134m	1.23E-12	8.39E-13	1.63E-9
Cs-135	1.22E-10	7.33E-11	
Cs-136	2.09E-10	1.26E-10	1.98E-7
Cs-137	8.54E-10	5.18E-10	
Cs-138	4.75E-12	3.51E-12	2.26E-7
Ba-131	4.59E-11	1.30E-11	3.91E-8
Ba-133	7.29E-11	1.09E-10	3.09E-8
Ba-133m	7.47E-11	1.51E-11	4.68E-9
Ba-137m	6.58E-14	4.24E-14	5.34E-8

Ba-139	8.23E-12	4.13E-12	3.02E-9
Ba-140	3.18E-10	8.57E-11	1.62E-8
La-140	2.56E-10	1.38E-10	2.18E-7
Ce-141	1.06E-10	1.17E-10	6.31E-9
Ce-143	1.60E-10	1.04E-10	2.24E-8
Ce-144	7.99E-10	2.91E-9	1.46E-9
Pr-142	1.89E-10	1.12E-10	5.52E-9
Pr-143	1.78E-10	1.51E-10	8.09E-16
Pr-144	2.18E-12	3.55E-12	3.18E-9
Pr-144m	8.72E-13	1.52E-12	3.39E-10
Nd-147	1.59E-10	1.31E-10	1.11E-8
Nd-149	1.23E-11	1.14E-11	3.24E-8
Pm-147	3.82E-11	2.02E-10	2.96E-13
Pm-148	3.90E-10	2.83E-10	5.25E-8
Pm-148m	2.68E-10	7.96E-10	1.78E-7
Pm-149	1.49E-10	9.64E-11	1.01E-9
Sm-147	6.78E-10	1.87E-7	
Sm-151	1.24E-11	1.25E-10	5.54E-14
Sm-153	1.09E-10	5.88E-11	3.88E-9
Eu-152	1.55E-10	2.14E-9	1.03E-7
Eu-154	2.53E-10	2.47E-9	1.14E-7
Eu-155	4.46E-11	2.59E-10	4.43E-9
Eu-156	2.95E-10	2.50E-10	1.30E-7
Gd-153	3.56E-11	8.66E-11	6.67E-9
Gd-159	7.03E-11	3.34E-11	3.14E-9
Tb-158	1.14E-10	1.90E-9	6.92E-8
Tb-160	2.06E-10	3.08E-10	9.85E-8
Dy-165	8.80E-12	6.06E-12	2.06E-9
Dy-166	2.55E-10	2.11E-10	2.36E-9
Ho-166	2.05E-10	1.10E-10	2.38E-9
Er-169	5.73E-11	4.08E-11	1.52E-13
Er-171	4.41E-11	2.03E-11	3.12E-8
Tm-170	2.03E-10	2.96E-10	3.47E-10
Tm-171	1.58E-11	4.97E-11	3.75E-11
Yb-169	9.27E-11	1.08E-10	2.27E-8
Yb-175	6.49E-11	4.54E-11	3.33E-9
Lu-177	7.97E-11	5.94E-11	2.89E-9
Hf-181	1.48E-10	1.67E-10	4.65E-8
Ta-182	1.90E-10	4.47E-10	1.17E-7
W-181	7.36E-12	2.17E-12	2.37E-9
W-185	5.50E-11	1.15E-11	2.27E-12
W-187	6.65E-11	1.43E-11	4.17E-8
Re-183	4.26E-11	6.94E-11	1.12E-8
Re-186	8.12E-11	7.06E-11	1.63E-9
Re-187	2.47E-13	5.10E-13	
Re-188	8.63E-11	6.25E-11	5.07E-9
Os-185	4.87E-11	1.25E-10	6.21E-8
Os-191	8.22E-11	7.30E-11	5.41E-9
Os-191m	1.34E-11	8.97E-12	3.03E-10
Os-193	1.18E-10	7.24E-11	5.59E-9
Ir-190	1.34E-10	1.21E-10	1.22E-7
Ir-192	1.74E-10	3.04E-10	7.06E-8
Ir-194	1.89E-10	1.13E-10	8.04E-9
Pt-191	4.05E-11	1.12E-11	2.32E-8
Pt-193	4.38E-12	2.13E-12	3.28E-12
Pt-193m	6.77E-11	1.56E-11	7.26E-10
Pt-197	5.74E-11	1.23E-11	1.79E-9
Pt-197m	8.79E-12	2.72E-12	6.28E-9
Au-196	3.52E-11	2.81E-11	3.97E-8
Au-198	1.43E-10	9.83E-11	3.49E-8
Hg-197	3.20E-11	1.88E-11	4.75E-9
Hg-203	7.15E-11	8.18E-11	1.94E-8
Tl-202	2.74E-11	1.64E-11	3.94E-8
Tl-204	5.33E-11	3.12E-11	7.68E-11

Tl-207	2.90E-13	3.34E-13	2.01E-10
Tl-208	4.73E-13	3.68E-13	3.54E-7
Tl-209	3.80E-13	3.04E-13	1.95E-7
Pb-203	2.79E-11	8.38E-12	2.50E-8
Pb-209	5.66E-12	1.85E-12	
Pb-210	1.82E-8	4.51E-8	9.09E-11
Pb-211	9.13E-12	2.79E-10	4.56E-9
Pb-212	4.87E-10	1.04E-9	1.23E-8
Pb-214	7.94E-12	1.68E-10	2.12E-8
Bi-206	1.92E-10	1.37E-10	3.01E-7
Bi-207	1.37E-10	2.54E-10	1.39E-7
Bi-210	1.97E-10	1.38E-9	
Bi-211	4.93E-13	4.71E-11	4.05E-9
Bi-212	1.68E-11	9.88E-10	1.69E-8
Bi-213	1.19E-11	8.36E-10	1.20E-8
Bi-214	5.27E-12	3.94E-10	1.44E-7
Po-210	8.80E-9	5.79E-8	7.79E-13
Po-212	1.22E-21	1.60E-19	
Po-213	1.81E-20	2.11E-18	2.79E-12
Po-214	5.74E-19	7.50E-17	7.63E-12
Po-215	1.35E-17	1.21E-15	1.29E-11
Po-216	2.38E-15	7.98E-14	1.33E-12
Po-218	1.37E-12	9.96E-11	
At-217	2.43E-16	1.39E-14	2.11E-11
Rn-219		1.87E-12	4.91E-9
Rn-220		5.18E-12	4.58E-11
Rn-222		4.96E-11	3.38E-11
Fr-221	3.91E-12	2.17E-10	2.61E-9
Fr-223	1.21E-11	1.60E-11	3.66E-9
Ra-223	6.33E-9	9.74E-8	1.11E-8
Ra-224	4.04E-9	6.08E-8	8.54E-10
Ra-225	4.25E-9	6.44E-8	4.40E-10
Ra-226	7.98E-9	7.35E-8	5.72E-10
Ra-228	6.64E-9	2.60E-8	4.77E-18
Ac-225	3.85E-9	1.12E-7	1.10E-9
Ac-227	9.52E-9	1.91E-6	1.01E-11
Ac-228	4.38E-11	8.84E-10	8.49E-8
Th-227	1.09E-9	1.16E-7	8.78E-9
Th-228	1.70E-9	2.55E-6	1.58E-10
Th-229	1.53E-9	2.05E-6	6.90E-9
Th-230	1.01E-9	4.66E-7	3.00E-11
Th-231	4.85E-11	2.97E-11	8.91E-10
Th-232	8.85E-10	5.21E-7	1.39E-11
Th-234	5.20E-10	5.15E-10	5.98E-10
Pa-231	4.02E-9	6.54E-7	2.54E-9
Pa-233	1.27E-10	1.33E-10	1.80E-8
Pa-234	5.76E-11	3.51E-11	1.78E-7
Pa-234m	1.29E-13	1.70E-13	1.05E-9
U-232	2.19E-9	1.43E-6	2.01E-11
U-233	1.21E-9	3.82E-7	1.91E-11
U-234	1.20E-9	3.77E-7	1.13E-11
U-235	1.22E-9	3.51E-7	1.28E-8
U-236	1.14E-9	3.57E-7	8.72E-12
U-237	1.08E-10	8.43E-11	1.08E-8
U-238	1.15E-9	3.36E-7	7.46E-12
U-240	1.48E-10	9.06E-11	4.84E-11
Np-236	2.52E-11	1.05E-10	1.06E-8
Np-237	7.98E-9	9.33E-7	1.79E-9
Np-238	1.23E-10	1.26E-10	5.11E-8
Np-239	1.15E-10	6.52E-11	1.38E-8
Np-240	4.79E-12	3.55E-12	1.04E-7
Np-240m	6.54E-13	7.64E-13	2.95E-8
Pu-236	2.08E-9	3.61E-7	8.30E-12
Pu-238	7.98E-9	7.42E-7	6.05E-12

Pu-239	8.53E-9	7.51E-7	6.29E-12
Pu-240	8.52E-9	7.51E-7	5.93E-12
Pu-241	1.40E-10	7.59E-9	
Pu-242	8.11E-9	7.13E-7	5.04E-12
Pu-243	9.97E-12	7.22E-12	1.82E-9
Pu-244	8.46E-9	7.20E-7	3.63E-12
Am-241	8.87E-9	1.04E-6	1.36E-9
Am-242	3.96E-11	2.81E-10	1.10E-9
Am-242m	7.90E-9	9.43E-7	3.42E-11
Am-243	8.84E-9	1.03E-6	3.85E-9
Cm-242	1.03E-9	8.54E-8	6.63E-12
Cm-243	6.79E-9	7.81E-7	1.05E-8
Cm-244	5.69E-9	6.58E-7	5.60E-12
Cm-245	9.05E-9	1.06E-6	5.75E-9
Cm-246	8.97E-9	1.05E-6	4.65E-12
Cm-247	8.35E-9	9.68E-7	2.72E-8
Cm-248	3.54E-8	3.95E-6	4.13E-12
Cf-252	4.86E-9	7.01E-7	5.04E-12

C7. AVERAGE VALUES USED IN THE INTERMEDIATE HEALTH RISK ASSESSMENT *(Taken directly from Genthe, 1998)*

- It is assumed that an adult weighs 70 kg.
- It is assumed that a child weighs 10 kg.
- It is assumed that a person drinks 2 liters of water a day.
- It is assumed that a person inhales 20 m^3 of air a day.
- It is assumed that the average lifetime of human is 70 years.

C8. EQUATIONS FOR MEMBERSHIP FUNCTIONS FOR THE INTERMEDIATE AND COMPREHENSIVE HEALTH RISK ASSESSMENTS

Membership functions for radiation and carcinogens are cosine graphs in the form:

$$\text{Membership} = \left[\frac{1}{2} \times (\cos(((I - U) * \pi / \text{stretch}) - \pi) + 1)\right]$$

where

Membership	=	A value between 0 and 1
I	=	Input (the value calculated by the DT radiogenic/carcinogenic risk)
U	=	Unfavourable limit
Stretch	=	Absolute value (favourable limit – unfavourable limit)

The cosine membership function for infection, toxin and size of exposed population is:

$$\text{Membership} = 1 - \left[\frac{1}{2} \times (\cos(((I - F) * \pi / \text{stretch}) - \pi) + 1) \right]$$

where

I = Input (the value given by the user for size of population OR the risks calculated by the DT for toxins and infection)

F = Favourable limit

APPENDIX D

Ecological Risk Assessment Information

D1. BREAKDOWN OF VEGETATION TYPES AND THEIR AVERAGE ROOT DEPTHS *(Taken directly from Scott and Le Maitre, 1998)*

Vegetation type	Mean root depth (m)
Trees - evergreen oaks, eucalypts	12.6
Trees - conifers	3.8
Trees - overall	7
Shrubs - evergreen, mediterranean	3.5
Shrubs - overall	5.1
Grasses and other herbaceous plants	2.6
Herbaceous crop plants	2.1
Desert trees and shrubs - evergreen or deciduous	9.5
Tropical savanna/grassland vegetation	15
Temperate grassland (prairie)	2.6
Tropical forest - evergreen	7.3

D2. GROUNDWATER-SURFACE WATER INTERACTION *(Taken directly from Scott and Le Maitre, 1998)*

Interaction	South African Rivers
Influent	Kuruman River from Frylinckspan Molopo River from Tshidilamolomo
Effluent	Upper reaches of perennial rivers Vaal River Olifants River Tugela River Blyde River Komati River
Intermittent	Streams in the Karoo Salt River Kamdeboo River Sundays River Brak River
Detached	Steeply graded and dry, rocky stream beds particularly in arid north-western parts of South Africa Noseob River

D3. BASE FLOW VALUES FOR PRIMARY CATCHMENTS *(Taken directly from Vegter and Pitman, 1996)*

Drainage region	Area (km^2)	MAP (mm)	MAR (10^6m^3)	MAR (mm)	MAR (%MAP)	Baseflow (10^6m^3)	Baseflow (mm/a)	Baseflow (%MAP)	Baseflow (%MAR)
A	109610	528	2176	19.9	3.8	690	6.3	1.2	31.7
B	73550	620	2651	36	5.8	758	10.3	1.7	28.6
C	196293	571	4298	21.9	3.8	606	3.1	0.5	14.1
D	409621	315	6987	17.1	5.4	947	2.3	0.7	13.6
E	49063	212	1008	20.5	9.7	102	2.1	1	10.1
F	28623	129	24	0.8	0.6	0	0	0	0
G	25312	476	1986	78.5	16.5	250	9.9	2.1	12.6
H	15530	545	2059	132.6	24.3	245	15.8	2.9	11.9
J	45134	260	662	14.7	5.6	50	1.1	0.4	7.6
K	7220	763	1307	181	23.7	298	41.3	5.4	22.8
I	34731	283	495	14.3	5	46	1.3	0.5	9.3
M	2630	555	151	57.4	10.3	10	6.6	1.2	6.6
N	21428	330	279	13	3.9	2	0.1	0.09	0.7
P	5322	560	174	32.7	5.8	4	0.8	0.1	2.3
Q	30243	410	519	17.2	4.2	29	1	0.2	5.6
R	7936	675	580	73.1	10.8	87	11	1.6	15
S	20485	610	1043	50.9	8.3	209	10.2	1.7	20
T	46684	860	7397	158.4	18.4	1526	32.7	3.8	20.6
U	18321	935	3128	170.7	18.3	868	47.4	5.1	27.7
V	29046	829	3994	137.5	16.6	770	26.5	3.2	19.3
W	59200	825	6533	110.4	13.4	2000	33.8	4.1	30.6
X	31157	715	3361	107.9	15.1	1370	44	6.1	40.8

D4. SARES PROGRAM *(Taken directly from Hughes, 1999)*

QC	Hz	Area	MAP	MAR	MAE	Reg #	%No flow	BF(mm)
A10A	1W	558	558	9.5	1950	18	49.64	0
A10B	1W	1013.1	529.1	7.5	1950	18	48.57	0
A10C	1W	270.9	537.1	8.1	1950	18	53.33	0
A21A	1F	482.8	683.5	33.6	1700	21	0	20.09
A21B	1C	526.5	671.8	19.1	1700	21	0	11.45
A21C	1F	761	682.2	49	1700	21	0	30.09
A21D	1C	371.5	713.7	56.3	1700	21	0	39.72
A21E	1F	289.8	706.4	54.6	1700	21	0	32.49
A21F	1K	1000.2	677.3	25	1700	21	0	12.1
A21G	1A	160.5	694.3	82.4	1700	21	0	62.7
A21H	1Q	513.7	668.2	36.3	1700	21	0	13.21
A21J	1Q	1150.2	637.4	18.6	1700	18	0	6.14
A21K	1K	864.1	717.7	100	1700	18	0	33.06
A21L	1Q	212.8	587.4	12.5	1750	18	0	4.55
A22A	1N	705.9	603.6	20.8	1800	18	0	7.37
A22B	1N	283.8	599.5	20.1	1800	18	0	7.18
A22C	1N	514.9	611	16.2	1750	18	0	6.17
A22D	1Q	541.3	582	14.6	1800	18	0	5
A22E	1Q	811.8	596.6	16.3	1800	18	0	5.5
A22F	1Q	1688.3	603.7	16.3	1800	18	0	5.46
A22G	1N	498.6	656.4	23.4	1700	18	0	8.49
A22H	1Q	578.7	657.7	23.7	1700	18	0	7.63
A22J	1Q	591.5	600.3	17.1	1750	18	0	5.56
A23A	1F	682.4	697.6	42.2	1750	21	0	25.06
A23B	1L	814.1	645.2	19.4	1800	21	0	9.37
A23C	1Q	491	573.8	8.8	1800	21	0	3.77
A23D	1A	144.8	706	114.9	1750	21	0	93.5
A23E	1L	490.4	674.2	29.3	1750	21	0	11.71
A23F	1Q	564.6	596.4	10	1800	21	0	4.21
A23G	1N	951.4	626.9	39.6	1750	21	0	11.75
A23H	1Q	1058.1	599.5	11.2	1750	18	0	4.55
A23J	1Q	930.3	585	9.8	1750	21	0	4.11
A23K	1Q	1130.8	606	13.1	1750	18	0	4.87
A23L	1Q	328.8	604.3	12.9	1750	18	0	4.75
A24A	1Q	493.1	598.6	14.5	1750	18	0	4.91
A24B	1Q	709.1	617.2	16.5	1750	18	0	5.61
A24C	1V	801.4	589.1	9.6	1800	18	46.07	0
A24D	1V	1326.5	599.8	11.7	1850	18	43.45	0.13
A24E	1V	687.7	592.4	11.5	1800	18	45.71	0

A24F	1V	590.7	602.3	12.5	1800	18	45.83	0
A24G	1N	735.3	644.8	28	1700	18	0	12.22
A24H	1Q	1338.2	638.5	34	1750	18	0	10.23
A24J	1V	2515.9	537.6	5.5	1900	18	44.05	0.04
A31A	1K	631.9	602.2	23.9	1850	18	0	11.79
A31B	1K	595.9	607.4	24.4	1850	18	0	11.95
A31C	1N	485	545.7	6.6	1900	18	0	2.84
A31D	1N	703.9	565.8	7.6	1900	18	0	3.14
A31E	1N	600.7	596.7	15.4	1900	18	0	5.69
A31F	1Q	701.5	591.2	15.4	1900	18	0	5.2
A31G	1Q	1425.1	583	15.1	1850	18	0	5.11
A31H	1W	683.6	578.8	10.7	1950	18	47.62	0
A31J	1W	844.1	552	8.7	1950	18	48.1	0
A32A	1W	472.3	546.5	9.2	1900	18	50.95	0
A32B	1W	640.9	569.3	11	1900	18	49.29	0
A32C	1W	901.7	526.5	7.5	1950	18	49.88	0
A32D	1W	842.7	533	8	1950	18	49.88	0
A32E	1W	2499.2	526	7.5	1950	18	47.26	0
A41A	1Q	691.9	625.3	34.6	1800	18	0.12	10.13
A41B	1Q	357.4	586.6	27.8	1800	18	0.12	8.31
A41C	1V	1110.7	511.7	7.8	1900	18	48.69	0
A41D	1V	1911.6	491.6	6.4	1950	18	48.21	0
A41E	1U	1938.3	438.2	5.9	1950	18	42.74	0.09
A42A	1H	573.4	639.9	45.2	1700	15	0	27.26
A42B	1H	521.6	659.9	49.8	1700	15	0	29.49
A42C	1H	698.3	655.5	48.8	1700	15	0	29.03
A42D	1M	496.6	667.3	93.5	1700	18	0	38.44
A42E	1M	1007.2	604.7	70.7	1700	18	0	29.68
A42F	1R	1021.7	577	36	1800	18	0	10.28
A42G	1R	1206.2	550.8	33.1	1900	18	0	9.39
A42H	1R	1056.6	517.6	26.2	1900	18	0	7.5
A42J	1U	1810.8	428.3	4.1	1950	18	43.45	0.05
A50A	1M	297.8	654.1	93.7	1700	18	0	37.55
A50B	1M	406.3	599	70.5	1750	18	0	29.09
A50C	1M	362.2	593	68.5	1750	18	0	28.37
A50D	1R	637.2	558.2	37.4	1850	18	0.12	10.54
A50E	1R	628.7	517	27.2	1900	18	0.12	7.72
A50F	1R	371.6	495.8	23.2	1900	18	1.19	6.43
A50G	1U	820.7	435.3	5.7	1950	18	47.86	0
A50H	1U	1944.7	407.1	4.5	1950	18	45.6	0
A50J	1U	1254.9	391.1	4	2000	18	48.45	0
A61A	1N	381.4	629.1	49.1	1700	18	0	18.31
A61B	1N	362.4	629.1	49.1	1700	18	0	16.14
A61C	1N	586.6	632.7	50.2	1741	18	0	14.15
A61D	1N	455.8	630.2	47.7	1734	18	0	14.34
A61E	1N	547.2	624.6	46.3	1738	18	0	13.35
A61F	1N	788.9	597.2	18.9	1800	18	0	8.25
A61G	1N	926.7	584.8	17.3	1800	18	0	7.73
A61H	1H	585.3	636	38.6	1700	19	0	20.5
A61J	1H	817.6	630.7	38.9	1750	19	0	19.5
A62A	1M	427.6	610.2	40.7	1800	18	0	19.26
A62B	1R	710	528.7	22.3	1850	18	0	6.63
A62C	1R	384.9	478.3	15.4	1900	18	0.24	4.73
A62D	1R	602.9	488.8	16.6	1900	18	0.12	5.1
A62E	1U	620.6	460.4	6.1	1850	18	45.36	0
A62F	1U	619.7	478.1	7.2	1850	18	44.52	0.03
A62G	1U	627	437.3	4.9	1900	18	45.95	0
A62H	1U	871.1	439.3	5	1900	18	45	0.01
A62J	1U	929.7	450.1	5.5	1950	18	43.93	0.05
A63A	1V	1927.7	433.1	8.5	1950	18	44.52	0.04
A63B	1V	1504.7	393.9	5.4	2000	18	46.67	0
A63C	1V	1323.1	377.7	4.6	2050	18	49.17	0
A63D	1V	1318.9	412.3	6.6	2000	18	46.31	0
A63E	1V	1991.7	357.9	3.8	2050	18	48.69	0
A71A	1U	1144.3	468.3	5.9	1800	18	42.14	0.11
A71B	1U	882	450.4	5.2	1700	18	45.12	0.01
A71C	1U	1330.7	417.8	3.9	1700	18	45.12	0.01
A71D	1U	891.8	390	3	1700	18	49.17	0
A71E	1U	892.9	420.8	4.5	1850	18	45.6	0
A71F	1U	682.8	400.2	3.7	1800	18	47.5	0
A71G	1U	875.1	427.2	4.9	1750	18	45.36	0
A71H	1U	1012.3	490.8	8.2	1550	18	41.43	0.19
A71J	1V	1161.9	396.1	6.9	1800	18	48.57	0
A71K	1X	1667.9	304.6	2.3	2000	18	55.48	0
A71L	1X	1764.6	287.8	1.9	2050	18	56.79	0
A72A	1U	1907.7	464.5	6.6	1900	18	40.83	0.18
A72B	1V	1554.4	343.9	3.7	1950	18	50.83	0
A80A	1P	287.4	938	160.4	1400	19	0	54.37
A80B	1P	251.3	659.3	49	1450	19	0	18.58
A80C	1P	293.6	576.3	27.3	1600	19	0	10.83
A80D	1P	127.7	621.9	40.2	1450	19	0	15.47

A80F	1V	629.7	388.1	6.1	1750	18	54.64	0
A80G	1X	1229.7	332.6	3.5	1900	18	53.93	0
A80H	1P	265.4	620.6	85.1	1750	18	0	33.83
A80J	1X	869.6	292.1	2.1	1900	18	59.76	0
A91A	1H	232.3	695.6	71.2	1400	17	0	37.52
A91B	1H	274.7	620.1	43.7	1600	17	0	24.79
A91C	1H	249.7	865.7	142	1500	17	0	82.3
A91D	1H	132.4	1287.3	377.3	1450	17	0	185.44
A91E	1H	223.1	980	251.3	1450	17	0	129.61
A91F	1S	579.8	602.3	34.6	1600	19	0	11.27
A91G	1H	405.8	863.7	340	1450	17	0	176.4
A91H	1S	449.9	656.4	58.8	1650	19	0	17.48
A91J	1X	569.8	449.9	10	1800	18	75.12	0
A91K	1X	669.3	372.1	4.2	1850	18	80.12	0
A92A	1H	328.9	831.2	360.1	1500	17	0	183.06
A92B	1S	565	645.7	55.9	1650	19	0	16.63
A92C	1X	454.7	423.4	10.8	1850	18	55.83	0
A92D	1X	804.5	301.2	2.6	1900	18	62.38	0
B11A	1L	945.4	699	38.9	1550	21	0	14.49
B11B	1L	435.3	687.3	36.2	1550	21	0	13.63
B11C	1L	385.4	672.7	33.2	1550	21	0	12.68
B11D	1L	550.9	671.5	30.1	1600	21	0	11.65
B11E	1L	466.7	682.4	32.2	1600	21	0	12.3
B11F	1L	428.3	691.6	34.3	1600	21	0	12.99
B11G	1L	367.8	692.5	35.8	1600	21	0	13.07
B11H	1L	246	694.8	36.3	1600	21	0	13.19
B11J	1J	269.4	681.6	48.7	1650	21	0	26.04
B11K	1J	378.3	683.8	46	1700	21	0	24.82
B11L	1J	241.8	692.1	47.9	1700	21	0	25.5
B12A	1L	406.9	672	26	1500	21	0	11.44
B12B	1L	658.5	696.9	28	1550	21	0	11.97
B12C	1L	529	706.6	29.9	1550	21	0	12.42
B12D	1L	362.3	702.7	38.1	1600	21	0	13.73
B12E	1J	435.8	696.8	52.5	1650	21	0	27.51
B20A	1J	574.3	661.2	37.9	1650	21	0	17.73
B20B	1J	321	667	37	1700	21	0	17.23
B20C	1J	363.7	675.2	38.2	1700	21	0	17.65
B20D	1J	480.4	677	36.1	1750	21	0	16.92
B20E	1J	619.9	657.3	33.9	1650	21	0	16.54
B20F	1J	504.2	666.8	33.3	1700	21	0	16.36
B20G	1J	522.4	669.3	44.1	1700	21	0	23.54
B20H	1J	562.5	670.8	41.5	1750	21	0	22.48
B20J	1J	407.4	695.8	44.3	1800	21	0	23.46
B31A	1L	386.6	676.8	35.2	1750	21	0	13.42
B31B	1L	385.1	640	25.8	1800	21	0	10.5
B31C	1L	373.4	607.5	20.8	1800	21	0	9.06
B31D	1L	557.6	599.3	19.8	1800	21	0	8.73
B31E	1V	1382.4	587.8	7.8	1800	18	49.4	0
B31F	1V	637.5	567.8	6.7	1850	18	52.02	0
B31G	1L	433.2	603.8	19.9	1850	21	0	8.33
B31H	1L	611.8	574.7	15.2	1900	21	0	6.91
B31J	1V	1379.9	551.7	5.9	1900	18	50.83	0
B32A	1J	801.4	690.7	51.7	1700	21	0	26.05
B32B	1J	613.8	697.8	51	1600	21	0	24.16
B32C	1J	302.8	664	36.4	1700	21	0	18.7
B32D	1M	521.1	625.8	22.7	1800	18	0.12	6.65
B32E	1M	203.2	668.4	33.7	1650	18	0.48	9.67
B32F	1M	667.2	658.7	29.1	1750	18	0	8.47
B32G	1L	967.6	639.1	25.8	1850	21	0	11.12
B32H	1L	693.9	609.6	20.2	1900	21	0	9.3
B32J	1T	322.8	589.2	13.9	1900	18	38.21	0.59
B41A	1G	764.5	714.5	64.7	1500	21	0	25.78
B41B	1G	778	704.8	61.9	1500	21	0	25.01
B41C	1G	302.4	694.3	58.8	1500	21	0	24.03
B41D	1G	402.9	651.5	41.1	1600	21	0	18.12
B41E	1T	237.1	616.3	17.5	1650	18	38.45	0.72
B41F	1G	379.8	675.9	73.6	1500	21	0	31.34
B41G	1G	442.1	650.2	65.9	1500	21	0	28.64
B41H	1T	410.3	621.4	18.2	1600	18	35.95	1.02
B41J	1T	690.8	598.1	21.9	1550	18	36.67	1.14
B41K	1T	635.2	625.9	26.8	1500	18	36.19	1.47
B42A	1E	318.9	773	109.5	1400	21	0	62.31
B42B	1E	213.7	878.9	156.1	1400	21	0	79.84
B42C	1M	164.1	728.8	50	1400	21	0	16.44
B42D	1E	154.6	1001.5	223.1	1400	21	0	103.11
B42E	1M	221.4	645	26.3	1450	21	0	9.75
B42F	1E	279.1	733	101	1450	21	0	56.88
B42G	1M	327.2	675.6	32.4	1450	21	0	11.53
B42H	1T	412.3	591.1	22.2	1450	18	37.98	0.98
B51A	1T	311.5	616.2	17.1	1800	18	37.14	0.84
B51B	1T	591.1	577.6	13.4	1900	18	36.55	0.71

B51E	1V	2926.8	542.1	6.8	1900	18	51.67	0
B51F	1T	394.6	573.4	16.1	1850	18	38.45	0.66
B51G	1T	590.7	527.8	12	1900	18	38.69	0.48
B51H	1T	717.3	567.5	12.8	1800	18	36.19	0.7
B52A	1T	566.1	475.2	8	1900	18	41.55	0.18
B52B	1T	632.9	552.5	14	1750	18	37.14	0.69
B52C	1U	200.4	539.1	15.9	1850	18	45.6	0
B52D	1T	341	497.6	9.5	1900	18	42.98	0.13
B52E	1T	450.8	535.1	12.2	1800	18	38.81	0.48
B52F	1U	118.4	556.8	17.9	1850	18	47.26	0
B52G	1U	290.9	518.1	13.7	1900	18	44.76	0.05
B52H	1U	563.3	660.1	36.2	1700	18	36.43	1.93
B52J	1U	394.7	569.8	19.6	1800	18	41.31	0.47
B60A	1B	209.4	1193.1	441	1400	17	0	299.2
B60B	1B	302.2	1026.3	349.2	1400	17	0	237.64
B60C	1B	94.1	1229.2	539.1	1400	17	0	318.76
B60D	1E	243.5	1003.9	218.2	1400	17	0	115.58
B60E	1E	83.4	1026.9	200.5	1400	17	0	109.33
B60F	1M	399.3	766.5	45.7	1400	19	0	17.84
B60G	1M	448	681.4	29.8	1400	19	0	12.22
B60H	1M	384.6	778	48.4	1400	19	0	18.54
B60J	1E	675.9	983	241.2	1482	19	0	71.11
B71A	1U	297.6	674.4	46.3	1650	18	37.26	2.24
B71B	1U	274.3	576.5	26.6	1650	18	41.79	0.57
B71C	1E	262.5	745.9	152.7	1500	17	0	86.32
B71D	1H	227.1	686.3	66.1	1550	17	0	39.73
B71E	1U	781.9	590.8	29.1	1650	18	36.55	1.53
B71F	1H	540.8	799.9	101.3	1500	17	0	54.98
B71G	1H	244.9	845.1	141.8	1450	19	0	67.51
B71H	1X	329.7	615	39.5	1450	18	63.81	0
B71J	1X	78.5	453.5	9.8	1550	18	81.19	0
B72A	1H	534	895	156	1500	19	0	51.8
B72B	1X	331.7	512	15.6	1550	18	71.43	0
B72C	1X	334.7	495.7	12.8	1500	18	73.45	0
B72D	1X	922.2	468.4	6.4	1600	18	72.02	0
B72E	1H	320.1	923.8	179.5	1500	19	0	58.17
B72F	1H	81.2	934.1	168	1500	19	0	76.04
B72G	1X	47.9	629.7	42.5	1500	19	62.74	0
B72H	1X	385.7	613.5	35.3	1550	18	65.24	0
B72J	1X	537.4	594	21.2	1600	18	64.88	0
B72K	1X	965.9	495.5	8.1	1650	18	69.4	0
B73A	1E	164.5	957	213.4	1450	17	0	98.43
B73B	1X	687.7	490.5	7.1	1650	18	71.43	0
B73C	1X	880	511.1	8.1	1750	18	69.52	0
B73D	1X	687	502.2	7.5	1750	18	70.71	0
B73E	1X	430.5	616.7	21.6	1600	18	64.4	0
B73F	1X	506.8	569.4	12.7	1800	18	67.5	0
B73G	1X	733.2	533.1	9.5	1850	18	68.33	0
B73H	1X	301.8	469.4	5.1	1900	18	75.71	0
B73J	1X	254.5	510.1	7.7	1900	18	73.33	0
B81A	1D	169.1	1194	378.3	1500	17	0	246.42
B81B	1D	481.2	1163.1	323.5	1500	17	0	201.84
B81C	1S	208.4	879.8	82.5	1500	19	0	32.42
B81D	1E	478.8	918.2	203.4	1500	17	0	83.16
B81E	1X	664.9	667.1	44.4	1550	19	60.71	0
B81F	1X	1199.7	544.5	15.7	1600	18	66.9	0
B81G	1X	512.4	626.7	31.5	1600	18	63.57	0
B81H	1X	667.7	510.1	10.7	1650	18	70.6	0
B81J	1X	567	501.8	9.4	1700	18	71.31	0
B82A	1S	466.6	720.6	49.6	1550	19	0	15.75
B82B	1S	406.3	702	44.6	1550	19	0	14.17
B82C	1S	299.7	712	47.3	1550	19	0	14.85
B82D	1S	631.7	622.9	26.2	1600	19	0	8.74
B82E	1S	423.4	656	32.1	1600	19	0	10.36
B82F	1S	759.8	676.3	36.3	1600	19	0	11.68
B82G	1X	920.1	523.7	15.5	1650	18	69.4	0
B82H	1X	748.6	516.3	14.4	1650	18	70	0
B82J	1X	793.7	539.6	17.2	1700	18	69.29	0
B83A	1X	1250	514.7	10.2	1750	18	67.14	0
B83B	1X	438.8	596.2	19.5	1750	18	65.6	0
B83C	1X	591.4	538.5	12	1850	18	67.62	0
B83D	1X	712.8	551.7	13.2	1850	18	66.31	0
B83E	1X	266.6	586.7	16.9	1900	18	67.14	0
B90A	1X	692.1	465.4	10.6	1750	18	71.9	0
B90B	1X	753.5	470.5	12.5	1650	18	71.67	0
B90C	1X	534.2	498.2	16.8	1650	18	71.19	0
B90D	1X	446.4	471.4	11.9	1700	18	72.86	0
B90E	1X	473.2	465.8	10.7	1750	18	72.86	0
B90F	1X	817.8	539	23.8	1650	18	67.98	0
B90G	1X	697.2	534.6	22.1	1700	18	68.57	0
B90H	1X	888.2	537.9	20.9	1800	18	67.86	0

C11B	2D	534.6	705.3	66	1400	20	0	19.4
C11C	2D	448.8	765.4	92.1	1400	20	0	26.47
C11D	2D	371.7	701.6	64.8	1400	20	0	19
C11E	2D	1154.7	696.8	62.8	1400	20	0	18.57
C11F	2D	929.1	704.7	60.5	1450	20	0	17.87
C11G	2D	431.7	658.8	44.7	1450	20	0	13.64
C11H	2F	1102.8	664	73.2	1500	20	0	20.03
C11J	2D	1000.6	657.9	53.1	1450	20	0	15.69
C11K	2F	339.9	633	59.7	1520	20	0	16.53
C11L	2D	946.9	675.3	58.8	1450	20	0	17.2
C11M	2D	795.2	637.5	42.9	1500	20	0	12.88
C12A	2D	484.1	614.4	41.4	1475	20	0	12.76
C12B	2D	478.4	631.2	42	1520	20	0	12.94
C12C	2D	665.6	605.2	37.2	1500	20	0	11.68
C12D	2F	898.3	666.9	59.3	1580	20	0	16.63
C12E	2F	497.3	640.7	53.5	1540	20	0	15
C12F	2F	834.1	634.9	49.1	1570	20	0	13.8
C12G	2F	570.4	640.3	52.4	1550	20	0	14.76
C12H	2F	355.1	618.4	34.9	1550	20	0.12	10.18
C12J	2F	344.3	615	34.7	1540	20	0.12	9.9
C12K	2F	478.7	657.3	44	1580	20	0	12.53
C12L	2F	886.5	647.9	40	1600	20	0	11.45
C13A	2D	593.5	778.8	87.7	1400	20	0	27.02
C13B	2D	615	682.9	51.2	1400	20	0	16.54
C13C	2D	836.2	723.6	65.5	1400	20	0	20.68
C13D	2D	894.6	698.3	56.2	1400	20	0	18
C13E	2D	602.1	698.8	56.6	1400	20	0	18.18
C13F	2D	610.6	692.1	49.5	1450	20	0	15.97
C13G	2D	434	673.6	45.8	1430	20	0	14.95
C13H	2D	588.4	627.7	31.2	1470	20	0	10.8
C21A	2F	706.6	674	62.1	1600	20	0	17.26
C21B	2C	430.6	697	37.5	1600	20	0	14.02
C21C	2C	437.8	673.6	32.3	1600	20	0	12.58
C21D	2C	445.8	698	36.1	1625	20	0	13.51
C21E	2C	628.2	690.7	34.5	1625	20	0	13.2
C21F	2C	426.6	703.7	37.5	1625	20	0	14.06
C21G	2C	462.4	665.9	29.5	1625	20	0	11.62
C22A	2C	548.4	695	31.5	1650	20	0	13.01
C22B	2C	391.5	691.4	31.7	1630	20	0	13.13
C22C	2C	465.2	683.8	30.7	1625	20	0	12.87
C22D	2C	345.2	700.5	32.6	1650	20	0	13.23
C22E	2C	532.1	668.9	28.1	1625	20	0	11.92
C22F	2C	440.2	655.4	24.3	1650	20	0	10.85
C22G	2C	830.3	612.8	19.9	1600	20	0	9.42
C22H	2C	454.1	639.5	21.9	1650	20	0	9.89
C22J	2C	668.7	632.7	21	1650	20	0	9.66
C22K	2C	433.8	644.4	23.6	1625	20	0	10.53
C23A	2E	258	612.5	32.1	1600	20	0	9.5
C23B	2E	701.1	619.5	33.3	1625	20	0	9.92
C23C	2E	1068.6	609	34.1	1650	20	0	10.08
C23D	2A	510.1	663.5	29.5	1650	23	0	21.54
C23E	2A	849.9	630.6	25.9	1675	23	0	19.48
C23F	2A	1323.6	605.4	23.5	1700	23	0	17.95
C23G	2A	613.1	597.4	22.9	1700	23	0	17.64
C23H	2A	451.2	603.5	23.4	1700	23	0	17.59
C23J	2E	890.3	620.2	38.3	1670	20	0	11.1
C23K	2E	395.9	606.7	35.1	1675	20	0	10.16
C23L	2E	1211	611.7	35.8	1700	20	0	10.4
C24A	2H	838.9	584	36.8	1750	20	0	10.45
C24B	2H	529.6	562.5	31.8	1750	20	0.12	9.04
C24C	2A	1349.8	586.7	23.1	1750	23	0	16.56
C24D	2H	364.2	584	27.6	1725	20	0.48	7.93
C24E	2H	925.4	559.8	22.3	1800	20	0	6.65
C24F	2H	2019.8	576.9	24.9	1830	20	0	7.32
C24G	2H	985.2	581.4	25.7	1820	20	0	7.5
C24H	2K	839.7	576.4	7.1	1820	18	47.02	0
C24J	2K	2109.4	552.3	5.7	1800	18	45.24	0
C25A	2K	863.4	541.9	6.5	1850	18	49.29	0
C25B	2K	1887.6	509.2	5	1750	18	48.81	0
C25C	2K	1209.6	522.2	5.4	1825	18	49.29	0
C25D	2K	1202.4	525.3	5.5	1860	18	49.17	0
C25E	2K	1536.1	509.9	4.7	1900	18	49.17	0
C25F	2K	2218.2	481.1	3.6	1850	18	49.64	0
C31A	2K	1402.2	577.2	10.7	1860	18	38.1	0.46
C31B	2K	1742.9	553.3	8.1	1900	18	38.45	0.33
C31C	2K	1635.1	565.9	9.2	1900	18	38.21	0.39
C31D	2K	1493.2	530.2	6.1	1925	18	40.12	0.19
C31E	2K	2958	506.2	7.8	1930	18	41.19	0.19
C31F	2K	1787.1	476.9	5.7	1960	18	45.12	0.01
C32A	2K	1403.3	449	8.2	1970	18	38.1	0.36
C32B	2K	2997.2	433.9	7.1	2000	18	36.19	0.39

C32D	2K	4133.8	441.6	7.5	2050	18	35.48	0.44
C33A	2K	2855.2	432.2	8.5	2070	18	37.62	0.39
C33B	2K	2830.5	422.2	7.8	2100	18	38.21	0.33
C33C	2K	4140.9	397.3	6	2150	18	38.21	0.26
C41A	2G	1077.7	598	55.6	1480	20	21.07	8.09
C41B	2G	1004.8	598	55.4	1500	20	21.07	8.06
C41C	2G	1094.6	594.5	54.3	1530	20	21.07	7.9
C41D	2G	1154.5	549.2	41.6	1560	20	22.86	5.61
C41E	2G	391.3	518.8	34.4	1580	20	28.21	3.53
C41F	2G	555.5	495.5	35	1600	20	31.43	2.92
C41G	2G	271.8	515.8	37.2	1600	20	33.33	2.68
C41H	2G	887.4	499.9	35.8	1680	20	30.6	3.17
C41J	2G	555.5	495.3	34.6	1700	20	31.43	2.89
C42A	2E	694.7	632.9	41.9	1440	20	0	13.35
C42B	2E	726.5	581.9	30.6	1460	20	0	10.03
C42C	2E	793.3	626.4	40	1450	20	0	12.79
C42D	2E	662.5	556.2	25.3	1500	20	0	8.42
C42E	2E	750.4	564.7	27.1	1480	20	0	8.92
C42F	2E	733.7	567.1	32.9	1540	20	0	10.37
C42G	2E	555	549.4	29.2	1560	20	0.12	9.28
C42H	2E	445	540	27.1	1590	20	0.24	8.51
C42J	2E	1013.9	529.8	25.3	1600	20	0	8.08
C42K	2E	668	521.2	23.8	1600	20	0.12	7.72
C42L	2E	510.8	505.9	22.7	1680	20	1.31	6.85
C43A	2K	1490.7	482.8	4	1780	18	48.45	0
C43B	2K	723.3	494.8	4.6	1730	18	49.88	0
C43C	2K	912.5	469.6	3.5	1830	18	50.83	0
C43D	2K	1475.4	464.6	3.4	1850	18	49.05	0
C51A	2J	675.1	474.2	28	1640	8	27.02	3.08
C51B	2J	1691.2	474.2	26	1660	8	23.45	3.41
C51C	2J	623.9	419.1	20.4	1725	8	29.52	1.94
C51D	2J	921.6	491	29.2	1640	8	32.38	2.27
C51E	2J	806	422.9	21.1	1730	8	28.21	2.17
C51F	2J	876.1	372.1	14.5	1800	8	32.74	1.1
C51G	2J	1834.5	402.7	19	1730	8	27.26	2.06
C51H	2J	1780.8	396.3	17.8	1800	8	27.86	1.87
C51J	2J	1050.8	387	16.4	1870	8	30.83	1.43
C51K	2M	3627.8	350.1	2.5	2000	8	55.83	0
C51L	2M	2029.2	349.9	2.5	2140	8	59.05	0
C51M	2M	1517.6	320.4	1.7	2200	8	65	0
C52A	2J	936.7	542.8	29.8	1600	8	31.07	2.55
C52B	2J	949.3	562.9	38.9	1570	8	22.62	5.3
C52C	2J	600.3	528.3	31	1600	8	26.55	3.49
C52D	2J	471.3	513.2	27.9	1620	8	28.21	2.87
C52E	2J	897.1	480.5	22.3	1620	8	26.79	2.48
C52F	2J	687.8	514.4	23.7	1670	8	33.21	1.72
C52G	2J	1788.6	481.4	24.5	1690	8	25	2.99
C52H	2L	2372.8	455	4.6	1800	8	45.24	0
C52J	2L	1922.3	456.3	4.7	1730	8	46.19	0
C52K	2L	4330.6	414.2	3	1900	8	46.55	0
C52L	2M	2403.8	377.4	3.3	2000	8	54.05	0
C60A	2E	859.4	625.1	40	1450	20	0	12.1
C60B	2E	1021.6	610.3	35.3	1480	20	0	10.7
C60C	2E	1047.4	571.4	25.8	1550	20	0	7.99
C60D	2E	644.7	550.4	23.4	1600	20	0.12	7.26
C60E	2E	663.9	557.1	24	1500	20	0	7.53
C60F	2E	659.1	556	24.7	1580	20	0.12	7.58
C60G	2E	781.6	536.9	21	1620	20	0.12	6.55
C60H	2K	1232	512.8	3.4	1650	18	49.05	0
C60J	2K	958.9	548.3	4.5	1700	18	47.86	0
C70A	2E	612.5	627.3	38.6	1500	20	0	11.49
C70B	2E	659.7	611.8	33.8	1550	20	0	10.26
C70C	2E	886.9	615.2	33.4	1600	20	0	10.11
C70D	2E	674.6	585.8	27.4	1600	20	0	8.41
C70E	2H	692.8	577.9	31.6	1630	20	0	9.36
C70F	2H	564.3	573.9	30.9	1620	20	0	9.25
C70G	2E	901.2	576.6	27.6	1600	20	0	8.46
C70H	2H	250.6	567.9	29	1650	20	0.71	8.59
C70J	2H	520.6	574.8	30.2	1670	20	0.12	8.97
C70K	2H	890.6	564.9	27.8	1690	20	0	8.33
C81A	2D	381.9	882.4	149.9	1350	20	0	45.35
C81B	2D	575.5	762.9	90.4	1350	20	0	28.48
C81C	2D	249.7	730.5	80	1320	20	0	25.73
C81D	2D	194.8	735.1	83.6	1310	20	0	26.61
C81E	2D	642.4	657.6	48.8	1360	20	0	16.61
C81F	2B	688	891.7	130.3	1300	20	0	44.05
C81G	2B	434.5	722	56	1310	20	0	21.72
C81H	2D	357.8	638.2	43.9	1350	20	0	15.3
C81J	2D	391.6	611.5	33.7	1410	20	0	12.29
C81K	2D	359.1	623.3	36.1	1410	20	0	12.99
C81L	2D	793.4	740.3	80.2	1350	20	0	25.63

C82A	2D	581.7	670.4	55.3	1400	20	0	18.56
C82B	2D	493	659.9	50.2	1420	20	0	17.03
C82C	2D	353	646.4	45	1430	20	0	15.39
C82D	2D	571.6	622.9	37.7	1440	20	0	13.36
C82E	2D	622	666.1	50.4	1440	20	0	17.01
C82F	2D	483.1	639.2	41.4	1450	20	0	14.41
C82G	2D	580.3	654.9	46.1	1450	20	0	15.68
C82H	2D	782.1	614.3	32.4	1490	20	0	11.73
C83A	2B	745.5	692.5	42.2	1350	20	0	17.45
C83B	2B	250.5	667.9	34.7	1380	20	0	14.83
C83C	2B	827.5	663.4	30.2	1440	20	0	13.23
C83D	2B	464.6	649.7	29.5	1410	20	0	13.14
C83E	2B	426	653.9	28.1	1450	20	0	12.42
C83F	2D	874.8	637.1	34.2	1480	20	0	12.27
C83G	2D	694.8	647.4	37.8	1460	20	0	13.42
C83H	2D	546.7	646	39	1480	20	0	13.37
C83J	2D	221.5	641.4	35.9	1510	20	0	12.28
C83K	2F	547.6	634.5	44.8	1520	20	0	13.76
C83L	2F	825.4	641.3	44.6	1550	20	0	13.59
C83M	2F	1100	639.2	41.9	1580	20	0	12.83
C91A	2L	2545	464.2	5	1940	18	48.45	0
C91B	2L	4675.9	432.8	3.7	1950	18	48.81	0
C91C	2L	3133.2	430.4	4.2	1880	18	50.12	0
C91D	2M	2693.9	397.3	3	2050	18	54.4	0
C91E	2M	1506.6	371.4	2.3	2140	18	59.76	0
C92A	2M	3913.5	367.3	7.8	2250	18	39.88	0.26
C92B	2M	1975.1	330.7	5.6	2225	18	46.55	0
C92C	2M	1953.7	325.9	5.2	2300	18	46.79	0
D11A	3A	278.2	1012.2	425.2	1300	13	0	167.41
D11B	3A	236.3	1056.3	307.2	1300	13	0	124.27
D11C	3A	291.5	909.1	329.1	1300	13	0	132.84
D11D	3A	318.6	902.3	233.5	1300	13	0	96.46
D11E	3A	322.3	737.2	177.6	1350	13	0	74.96
D11F	3A	413	700.5	241.2	1350	13	0	98.04
D11G	3A	319.7	780.3	200.3	1300	13	0	86.74
D11H	3A	358.3	683.5	193	1300	13	0	81.41
D11J	3A	439.6	659.4	142.5	1350	13	0	62.65
D11K	3A	380.9	623.2	135.2	1350	13	0	59.69
D12A	3B	369.1	627	89.7	1600	20	0	36.42
D12B	3B	385.1	719.8	133.8	1545	9	0	51.21
D12C	3E	342.9	637.9	47.5	1600	8	27.98	4.95
D12D	3E	355.3	605.2	40	1575	8	29.4	3.82
D12E	3E	711.9	593.4	36.9	1600	8	27.74	3.9
D12F	3E	803.2	545	27.1	1600	8	29.29	2.61
D13A	3B	474.8	809.1	144.4	1475	11	0	65.04
D13B	3B	532.9	785.2	133.6	1475	11	0	60.75
D13C	3B	517	703.6	102.1	1475	11	0	48.76
D13D	3B	635.1	675.5	87.9	1525	9	0	43.05
D13E	3B	1030.9	754.4	120.8	1475	9	0	56.08
D13F	3B	969.9	666.3	96.1	1600	9	0	42.48
D13G	3E	1124.9	631.4	45.4	1600	8	22.5	6.22
D13H	3E	1144.1	537.5	25.2	1625	8	25.71	2.97
D13J	3E	1167	549.8	27.3	1625	8	25.24	3.29
D13K	3B	397.2	732.2	122.4	1575	9	0	51.53
D13L	3E	681.6	592.6	35.8	1625	8	25.12	4.34
D13M	3E	678	538.2	25.2	1625	8	28.45	2.55
D14A	3F	764.4	493	27.7	1675	8	33.57	1.95
D14B	3E	323.9	486.6	21	1700	8	35.71	1.21
D14C	3E	721.5	491.2	21.6	1700	8	30.71	1.89
D14D	3E	679.8	443	14.6	1700	8	35.6	0.85
D14E	3E	663.3	431.2	13.1	1700	8	36.31	0.71
D14F	3E	540.9	491.8	22.2	1650	8	32.5	1.71
D14G	3E	605.4	519.5	27.3	1650	8	29.64	2.57
D14H	3F	697.1	435	17.9	1675	8	36.9	0.91
D14J	3F	514.9	436	18.1	1675	8	38.45	0.75
D14K	3F	633.9	426.6	16.7	1675	8	38.1	0.73
D15A	3B	436.9	698.2	248.1	1450	11	0	99.61
D15B	3B	393.3	731.2	240.5	1450	11	0	96.87
D15C	3B	275.9	705	179	1450	11	0	73.95
D15D	3B	436.9	725.4	220.6	1450	11	0	89.3
D15E	3B	618.7	719.8	169.3	1500	11	0	64.19
D15F	3D	352.4	696.3	78.7	1500	20	0.24	22.66
D15G	3D	484.7	670.2	53.6	1500	20	0.12	15.57
D15H	3D	360.8	608.5	37.7	1525	20	0.48	11.07
D16A	3A	159.2	913.9	408.2	1300	13	0	165.17
D16B	3A	248	854	336.5	1300	13	0	137.12
D16C	3A	437.2	652.4	113.7	1350	13	0	54.38
D16D	3A	339	881.8	279.1	1300	13	0	107.69
D16E	3A	433.5	637.4	176	1300	13	0	72.45
D16F	3A	276.4	604.5	281.2	1300	13	0	108.57
D16G	3A	289.4	616	244.8	1300	13	0	96.2

D16J	3A	373.6	617.8	195.7	1350	13	0	78.74
D16K	3A	328.7	622.3	189.7	1350	13	0	80.04
D16L	3A	532.7	558.8	116.1	1350	13	0	53.47
D16M	3A	752.8	669.4	85	1350	13	0	41.54
D17A	3A	638	697.4	258.3	1375	11	0	112.7
D17B	3A	441.8	726.2	257.7	1375	11	0	112.42
D17C	3A	524.6	672.1	181.5	1400	11	0	82.43
D17D	3A	748	591.6	184.4	1450	11	0	83.09
D17E	3A	604.7	538.6	196	1450	11	0	87.26
D17F	3A	582	585.2	101.7	1450	11	0	50.18
D17G	3A	848.4	553.4	108	1400	11	0	48.18
D17H	3A	851	573.8	100.5	1400	11	0	45.62
D17J	3A	436.8	571.5	192.4	1375	11	0	78.62
D17K	3A	383.1	667.8	111.7	1375	11	0	49.41
D17L	3A	589.9	664.1	95.8	1400	11	0	44.1
D17M	3A	528.2	570.2	104.5	1450	11	0	46.74
D18A	3B	599	586.8	147.6	1475	11	0	65.48
D18B	3B	327.1	683	111.3	1475	11	0	51.36
D18C	3B	465.4	690.7	94	1475	11	0	44.84
D18D	3B	765.9	615.5	133.3	1475	11	0	59.87
D18E	3B	375.7	697.6	135.1	1475	11	0	60.47
D18F	3B	445.7	678.2	89.2	1475	11	0	43.06
D18G	3B	491.6	767.3	160.4	1500	11	0	63.28
D18H	3B	383.6	714.3	119.5	1500	11	0	49.36
D18J	3B	858.6	712.2	118.9	1500	11	0	49.16
D18K	3B	935	774.3	144	1525	9	0	57.75
D18L	3B	609.6	663	96.4	1525	11	0	41.02
D21A	3C	309.3	977.9	203.2	1275	20	0	82.32
D21B	3C	393.7	1021.2	229.4	1275	20	0	90.98
D21C	3C	211.6	883.1	150	1275	20	0	64.34
D21D	3C	251.5	839.3	124.2	1300	20	0	55.02
D21E	3C	268.3	784.4	100	1300	20	0	46.58
D21F	3D	479.5	724.9	69.4	1325	20	0	20.16
D21G	3D	278.1	751	78.8	1325	20	0	22.7
D21H	3C	380.8	782.5	104.2	1325	20	0	46.85
D21J	3C	359.3	990.5	211.7	1300	20	0	83.29
D21K	3C	325.9	960.3	193.6	1300	20	0	76.97
D21L	3C	304.2	859.8	136.2	1325	20	0	57.54
D22A	3D	635.4	681.7	57.4	1375	20	0	16.68
D22B	3D	457	724.6	71.6	1375	20	0	20.44
D22C	3C	485.4	782.3	103.3	1375	20	0	44.82
D22D	3D	627.7	694.2	59.9	1400	20	0	17.21
D22E	3C	498.1	816.6	105	1475	20	0	45
D22F	3C	632.8	758.3	83.6	1475	20	0	37.5
D22G	3D	969.3	687.8	55.8	1450	20	0	16.09
D22H	3D	540.9	730.5	68	1450	20	0	19.58
D22J	3C	651.7	772	97.1	1400	20	0	42.79
D22K	3C	323.7	749.5	88.9	1400	20	0	39.92
D22L	3D	376.4	705	58.8	1475	20	0.12	17.12
D23A	3D	608	687.5	64.3	1475	20	0.24	18.33
D23B	3D	596.9	705.2	69.8	1475	20	0.24	19.8
D23C	3D	861	637.9	48.5	1500	20	0.24	13.96
D23D	3D	564.9	607.2	39.8	1525	20	0.24	11.54
D23E	3D	702.2	614.9	41.7	1525	20	0.24	12.08
D23F	3D	351.6	638.3	56.8	1525	20	0.6	16.04
D23G	3D	511.6	621.7	52.3	1525	20	0.6	14.82
D23H	3E	776	519	26	1600	20	30.6	2.3
D23J	3D	533.6	541.1	30.7	1550	20	30.83	2.67
D24A	3D	309.9	627.3	51.9	1575	8	1.07	14.5
D24B	3E	470.5	590.6	41.1	1575	8	28.57	4.13
D24C	3E	398.1	531.9	28.6	1575	8	31.55	2.37
D24D	3E	598.4	490.2	21.2	1575	8	32.02	1.69
D24E	3E	489.1	490.5	21.3	1575	8	33.45	1.52
D24F	3E	567	519.5	26.1	1575	8	30.71	2.29
D24G	3E	626	524.5	30.2	1650	8	31.43	2.52
D24H	3F	735.7	478	21.7	1650	8	33.45	1.55
D24J	3F	1032.3	446.6	16.9	1650	8	34.52	1.1
D24K	3F	877	442	16	1650	8	35.6	0.93
D24L	3F	510.6	433.8	15.1	1650	8	38.69	0.6
D31A	3G	1158.7	395.6	11	1900	8	42.26	0.2
D31B	3G	994.9	313.5	4.3	1900	8	52.38	0
D31C	3G	676.2	328.4	5.2	1900	8	52.74	0
D31D	3G	1107.3	377	9.1	1900	8	45.12	0.01
D31E	3G	968.4	352.8	6.9	1900	8	48.1	0
D32A	3G	714.7	314.1	4.5	1925	8	54.29	0
D32B	3G	580.9	340.6	6.4	1925	8	51.67	0
D32C	3G	849	316	4.6	1925	8	52.86	0
D32D	3G	849.6	311.9	4.3	1925	8	53.69	0
D32E	3G	1155.2	274.2	2.6	1925	8	57.86	0
D32F	3G	1441.2	304.7	4	1900	8	51.07	0
D32G	3G	1043.9	330.2	5.5	1900	8	49.4	0

D32J	3G	1112.5	314.7	4.6	1900	8	51.31	0
D32K	3G	823.4	324.1	5.1	1900	8	51.55	0
D33A	3G	592.1	333.4	3	2075	8	50.95	0
D33B	3G	1016.5	315.2	2.6	2075	8	50.24	0
D33C	3G	804.1	333.1	3.1	2075	8	49.29	0
D33D	3G	950	298.9	2.1	2075	4	52.86	0
D33E	3G	1551.7	307	2.3	2100	4	48.81	0
D33F	3G	861.2	288.2	1.7	2100	4	54.76	0
D33G	3G	1403.5	284.7	1.7	2200	4	52.86	0
D33H	3G	1052.2	297.9	2	2200	4	52.14	0
D33J	3G	862.9	272.1	1.4	2200	4	57.86	0
D33K	3G	487	286.8	1.8	2200	4	59.17	0
D34A	3G	793.3	384.9	10.7	1750	8	45	0.02
D34B	3G	705.4	360.9	7.9	1800	8	48.21	0
D34C	3G	760	343.4	6.4	1800	8	49.52	0
D34D	3G	598.9	349.2	7	1800	8	50.12	0
D34E	3G	518.8	363.8	8.3	1800	8	49.64	0
D34F	3G	691.3	337.7	6.1	1800	8	50.71	0
D34G	3G	948.8	372	9.1	1800	8	45.12	0.01
D35A	3G	254.4	435.5	14.6	1700	8	46.19	0
D35B	3G	260.1	422.6	13.1	1700	8	47.38	0
D35C	3G	943	407.8	9.7	1725	8	39.88	0.32
D35D	3G	586.2	390.4	8	1725	8	44.76	0.03
D35E	3G	312	402.6	10.6	1725	8	47.86	0
D35F	3G	557.2	425.2	13.1	1725	8	42.62	0.21
D35G	3G	551.7	386.6	7.6	1750	8	45	0.02
D35H	3G	498.1	400.8	10.2	1725	8	45.48	0
D35J	3G	1001.1	371.1	6.5	1750	8	43.21	0.08
D35K	3G	674	385.1	8.6	1725	8	45.36	0
D41A	3H	4298	509.3	6.3	1950	18	43.81	0.06
D41B	3J	6164	443	2	1950	18	57.38	0
D41C	3J	3907.2	396.3	1.1	2050	18	62.98	0
D41D	3J	4369.4	380.2	1	2050	18	64.17	0
D41E	3J	4490.6	334.1	0.5	2250	18	71.55	0
D41F	3J	6001.5	331.8	0.5	2250	18	70.6	0
D41G	3H	4304.7	365.5	1.4	2200	18	54.4	0
D41H	3J	8646.5	323.9	0.4	2250	18	71.55	0
D41J	3H	3873.5	357.7	1.3	2350	18	55.48	0
D41K	3H	4212.7	344.1	1	2350	18	56.43	0
D41L	3H	5374.7	391.3	1.8	2250	18	51.79	0
D41M	3H	2625.8	304.6	0.6	2400	18	62.5	0
D42A	3M	10273.9	222.2	0.5	2900	4	85.12	0
D42B	3M	3197.7	176.3	0.2	2950	4	92.38	0
D42C	3M	18107.9	215.7	0.4	2700	4	85.48	0
D42D	3M	16208.7	150.6	0.1	2750	4	93.33	0
D42E	3L	4207.5	148	0.1	2750	4	94.64	0
D51A	3K	796.9	311.5	11.9	1950	4	42.5	0.2
D51B	3K	873	239.8	4.2	1950	4	50.24	0
D51C	3K	522.1	176.2	1.3	1950	4	65.6	0
D52A	3K	377.6	319.2	11.9	1900	4	46.9	0
D52B	3K	660	267.2	6.4	1900	4	48.81	0
D52C	3K	465.3	192.7	1.5	1900	4	63.69	0
D52D	3K	638.3	245.7	4.7	1900	4	51.67	0
D52E	3K	608.5	194.4	1.6	1900	4	61.31	0
D52F	3K	1145.7	161.5	1	1950	4	60.36	0
D53A	3L	1938.5	159.9	2.9	2475	4	65.24	0
D53B	3L	1713.2	167.3	3.3	2475	4	64.05	0
D53C	3L	1899.3	148.9	2.3	2300	4	67.98	0
D53D	3L	1841.7	136.2	1.7	2300	4	70.48	0
D53E	3L	825.8	140.5	1.8	2300	4	73.93	0
D53F	3K	8036.6	89.9	0.4	2450	4	76.19	0
D53G	3L	4745.5	98.6	0.5	2300	4	75.71	0
D53H	3L	1589.3	131.3	1.4	2300	4	73.1	0
D53J	3L	454.9	134.3	1.5	2300	4	78.21	0
D54A	3K	1517.9	144.2	2.8	2325	4	59.88	0
D54B	3K	4051.3	190.6	3.7	2325	4	51.55	0
D54C	3K	1342.2	154.9	1.8	2325	4	64.17	0
D54D	3K	5069.6	172.6	2.6	2450	4	55.83	0
D54E	3K	3325.5	163.3	2.1	2325	4	58.81	0
D54F	3K	3808.5	161.3	2	2450	4	60.12	0
D54G	3K	4502.6	169.3	2.4	2450	4	57.14	0
D55A	3K	1871.6	221.2	3.2	2150	4	46.19	0
D55B	3K	1259.4	187.4	1.7	2150	4	54.88	0
D55C	3K	760.4	217	5	2150	4	55.36	0
D55D	3K	1888.7	190.7	3.3	2150	4	54.17	0
D55E	3K	2240.2	172.7	1.3	2150	4	54.05	0
D55F	3K	2631.1	176.1	2.5	2300	4	55	0
D55G	3K	1292.8	170.9	2.2	2300	4	60.12	0
D55H	3K	1151.2	158.1	1.7	2300	4	63.81	0
D55J	3K	1998.3	161.9	1.8	2300	4	60.36	0
D55K	3K	1247	157.9	1.6	2300	4	63.1	0

D55M	3K	1812.6	143.5	1.2	2300	4	64.64	0
D56A	3K	510.2	223.3	7.1	1950	4	48.21	0
D56B	3K	518.6	266.1	5	1950	4	50.71	0
D56C	3K	920.5	223.3	3.5	1950	4	50	0
D56D	3K	620.8	189.2	1.4	1950	4	61.31	0
D56E	3K	665.6	228.8	4.5	2000	4	52.26	0
D56F	3K	1038.4	191	2.4	2000	4	56.55	0
D56G	3K	651.2	176.5	1.8	2000	4	62.74	0
D56H	3K	447.3	174	1.1	1950	4	66.9	0
D56J	3K	930.8	167.2	1.5	2000	4	62.14	0
D57A	3K	853.3	125.7	0.7	2200	4	71.67	0
D57B	3K	2273.9	147.4	1.3	2200	4	64.17	0
D57C	3K	636.6	126.4	0.8	2200	4	73.33	0
D57D	3K	4443.7	137.7	1.6	2450	4	62.38	0
D57E	3K	1957.4	145.4	1.8	2450	4	65.71	0
D58A	3K	763.3	144.2	0.7	2100	4	69.29	0
D58B	3K	1131.1	162.8	1	2100	4	60.12	0
D58C	3K	2520.2	136	0.5	2100	4	61.55	0
D61A	3G	1463.9	275.3	3	2100	4	55.12	0
D61B	3G	1196.4	272.2	2.8	2100	4	57.14	0
D61C	3G	1168.5	246.8	2	2100	4	61.9	0
D61D	3G	650.1	242	1.8	2100	4	66.67	0
D61E	3G	1089.6	230.5	2.4	2250	4	66.55	0
D61F	3G	872.9	203.5	1.5	2250	4	71.79	0
D61G	3G	743.3	215.9	1.9	2250	4	70.24	0
D61H	3G	1085.2	231	2.4	2250	4	66.55	0
D61J	3G	1557.4	214.8	1.9	2250	4	66.79	0
D61K	3G	1606.7	226.8	2.2	2250	4	64.05	0
D61L	3G	1014.5	270.1	2.8	2100	4	59.52	0
D61M	3G	941.7	252.4	3.3	2250	4	63.1	0
D62A	3G	2240.4	248.1	1.8	2150	4	59.05	0
D62B	3G	3114	220.7	2	2150	4	64.17	0
D62C	3G	2126	278.4	2.8	2150	4	54.4	0
D62D	3G	2396.8	299.1	3.7	2150	4	51.07	0
D62E	3G	1920.1	272.8	2.6	2150	4	56.07	0
D62F	3G	1697.5	290	3.2	2150	4	53.69	0
D62G	3G	2545.3	255.6	3.4	2350	4	58.93	0
D62H	3G	2060.8	215.6	1.8	2350	4	66.55	0
D62J	3G	2197.8	231.3	2.3	2350	4	63.69	0
D71A	3G	1207.8	282.8	4.7	2350	4	57.98	0
D71B	3G	2871.3	315.5	7	2350	4	50.6	0
D71C	3G	1590.2	249.9	3	2350	4	61.07	0
D71D	3G	1711.9	247.6	2.9	2350	4	61.07	0
D72A	3G	1395.9	210.4	2.2	2350	4	67.98	0
D72B	3L	2568	214.6	4.9	2475	4	50.48	0
D72C	3L	2774.9	200.1	3.9	2475	4	52.62	0
D73A	3L	3234.8	322.7	14.6	2450	4	38.45	0.6
D73B	3L	3718.9	258.3	7.1	2450	4	44.64	0.03
D73C	3L	6217.9	230.4	4.8	2450	4	45.24	0
D73D	3L	4290.4	185.2	3.6	2650	4	54.05	0
D73E	3L	3866.7	182.5	3.4	2650	4	54.52	0
D73F	3L	4629.9	158.2	2.1	2650	4	59.64	0
D81A	3L	2310.4	127.8	1.2	2700	4	70.48	0
D81B	3L	851	113.2	0.7	2750	4	77.62	0
D81C	3L	2681.7	119.6	0.9	2750	4	72.26	0
D81D	3L	1825.6	113.1	1.1	2750	4	73.33	0
D81E	3L	1290	97	0.6	2750	4	79.52	0
D81F	3L	1839.9	91.3	0.5	2750	4	79.76	0
D81G	3L	2006	101.6	0.4	2650	4	73.69	0
D82A	3P	1915	76.9	0.2	2650	3	83.93	0
D82B	3P	4872.5	80.3	0.2	2650	3	77.98	0
D82C	3P	3990.5	82.9	0.2	2650	3	77.74	0
D82D	3P	2961.5	110.8	0.6	2650	3	68.69	0
D82E	3P	941.9	100	0.7	2550	3	78.81	0
D82F	3P	1036.3	105.9	0.9	2400	3	76.43	0
D82G	3P	592.7	78.9	0.3	2400	3	86.67	0
D82H	3P	819.3	60.1	0.1	2400	3	90.48	0
D82J	3P	1380.5	29	0	2400	3	98.21	0
D82K	3P	913.7	31.2	0	2200	3	98.33	0
D82L	3P	750.3	42.1	0	2200	3	96.31	0
E10A	4E	133.7	898.6	458.2	1650	1	2.02	133.9
E10B	4E	202	736.3	345.5	1650	1	2.02	100.13
E10C	4E	192.5	586.9	259.4	1640	1	2.5	74.22
E10D	4E	234.9	518.4	208.5	1640	1	2.62	58.91
E10E	4E	365.8	419	143.2	1640	1	3.1	39.48
E10F	4E	385.8	407	136.3	1645	1	3.21	37.24
E10G	4E	508.3	407.5	136	1650	1	2.14	38.14
E10H	4E	162.2	494.9	206.8	1680	2	4.76	55.76
E10J	4L	468.3	344	64.1	1675	2	1.31	19.25
E10K	4X	235.3	283.6	20	1690	2	90.36	0
E21A	4L	190	620	183.7	1660	2	1.67	56.91

E21C	4L	233.2	466.8	107.3	1675	2	2.26	32.56
E21D	4L	241.9	626.6	187.6	1665	2	1.43	58.53
E21E	4L	292.8	360.3	66.9	1680	2	1.43	20.41
E21F	4L	378.6	288.9	43.5	1690	2	1.55	13.42
E21G	4L	266.1	475.1	115	1655	2	0.6	35.93
E21H	4L	404.3	428.5	94.3	1670	2	0.36	29.51
E21J	4L	316.6	338	59.3	1680	2	1.43	18.22
E21K	4L	330.3	351.9	65.2	1680	2	1.67	19.24
E21L	4X	194.9	216.1	6.7	1700	3	56.67	0
E22A	4X	750.3	250.6	10.8	1920	3	40.48	0.31
E22B	4X	637.6	249.2	10.8	1850	3	41.67	0.24
E22C	4X	489.5	323.9	27.3	1690	3	34.76	1.73
E22D	4X	495.7	226.1	7.9	1760	3	47.5	0
E22E	4X	1013.2	212.3	6.4	1725	3	45.36	0
E22F	4X	400.4	162.9	2.5	1715	3	63.1	0
E22G	4X	367	172.7	3	1730	3	61.43	0
E23A	4X	761.6	253.9	10.1	1895	3	40	0.32
E23B	4X	705	240.4	8.4	1870	3	42.62	0.14
E23C	4X	317.7	212.8	5.7	1850	3	52.98	0
E23D	4X	750.2	219	6.3	1850	3	45.36	0
E23E	4X	564.1	265.1	11.7	1870	3	40.36	0.35
E23F	4X	472.7	134.4	1.1	1835	3	68.69	0
E23G	4X	747.5	189.5	4.3	1810	3	51.43	0
E23H	4X	660.1	204.9	5.5	1820	3	48.57	0
E23J	4X	894.8	138.6	1.3	1805	3	63.81	0
E23K	4X	571.7	126.3	0.9	1800	3	69.88	0
E24A	4X	254.7	392.6	67.8	1695	3	25.24	8.17
E24B	4X	467.6	272.4	22	1725	3	29.76	2.06
E24C	4X	783.9	235.3	13	1880	3	28.57	1.31
E24D	4X	997.4	178.2	5.7	1845	3	33.57	0.4
E24E	4X	671.2	203.6	8.6	1890	3	33.57	0.61
E24F	4X	582.3	192.4	7.2	1895	3	36.19	0.39
E24G	4X	632.7	174	6	1845	3	39.4	0.21
E24H	4X	482.5	190.1	8.3	1795	3	39.4	0.3
E24J	4X	1077.7	235.2	19	1800	3	28.21	1.95
E24K	4X	651.9	237.7	15.6	1860	3	31.79	1.27
E24L	4X	515.8	310.6	45	1745	2	2.38	13.12
E24M	4X	528.5	265	18.5	1760	3	45.71	0
E31A	4X	2865.2	83.7	0.1	2230	3	78.45	0
E31B	4X	1476.3	150.9	1.1	2100	3	55.36	0
E31C	4X	1572.1	112.6	0.4	2150	3	68.69	0
E31D	4X	839.2	113.8	0.4	2105	3	71.67	0
E31E	4X	477.9	156.9	1.3	2080	3	61.9	0
E31F	4X	524.8	174.7	1.9	2025	3	57.14	0
E31G	4X	1237.9	109.8	0.3	2090	3	70.6	0
E31H	4X	726.1	149.8	1.1	2015	3	60.83	0
E32A	4X	1117.7	206.5	3.4	2020	3	45.48	0
E32B	4X	828.2	183.5	2.2	2000	3	51.55	0
E32C	4X	638.1	227.2	4.7	1950	3	45.83	0
E32D	4X	615.8	175.8	1.9	2005	3	55.36	0
E32E	4X	1001.1	192.6	2.6	1950	3	48.33	0
E33A	4X	1354.7	135.9	0.7	2000	3	60.6	0
E33B	4X	701.9	113.9	0.4	1910	3	75.24	0
E33C	4X	980.1	139.7	1	1880	3	63.81	0
E33D	4X	1558.9	131.4	0.8	1905	3	63.57	0
E33E	4X	1282.3	124.2	0.6	1835	3	66.9	0
E33F	4X	724.7	212.3	4.6	1835	3	50.12	0
E33G	4X	894.3	186	2.8	1760	3	51.9	0
E33H	4X	718.4	133.8	0.8	1730	3	67.62	0
E40A	4X	941	235.7	7.9	1940	3	43.33	0.09
E40B	4X	707.5	240.7	8.5	1945	3	44.64	0.04
E40C	4X	530	285.3	12.8	1905	3	41.67	0.28
E40D	4X	544	284.3	12.9	1850	3	41.67	0.28
F10A	4P	458.5	64.3	0	2250	3	91.55	0
F10B	4P	1084.9	62.1	0.1	2250	3	89.52	0
F10C	4P	1171.1	53	0.1	2250	3	91.79	0
F20A	4P	1116.9	98.6	0.4	2100	3	77.62	0
F20B	4P	512.5	91.1	0.4	2100	3	83.81	0
F20C	4P	611	79.6	0.2	2100	3	86.19	0
F20D	4P	453.1	71.2	0.2	2100	3	89.64	0
F20E	4P	433.5	91.9	0.5	2100	3	84.29	0
F30A	4N	1950.9	161.9	1.4	2200	3	56.79	0
F30B	4N	1459.9	107.4	0.3	2200	3	74.64	0
F30C	4N	1651.2	184.3	2.2	2200	3	53.45	0
F30D	4N	973.6	162.3	1.4	2200	3	60.36	0
F30E	4N	1257.2	152.7	1.2	2200	3	60.95	0
F30F	4P	1464.6	112.4	0.4	2200	3	73.1	0
F30G	4P	977.1	102	0.3	2200	3	79.4	0
F40A	4P	980.5	117.9	0.4	1900	3	72.74	0
F40B	4P	403.3	130	0.5	1900	3	75.36	0
F40C	4N	606.7	173.3	1.5	1900	3	63.81	0

F40E	4N	1061.9	185.6	2	1900	3	56.79	0
F40F	4P	680	117.8	0.4	1900	3	75.12	0
F40G	4N	347.3	168.2	1.4	1900	3	67.5	0
F40H	4P	512.6	108.7	0.2	1900	3	78.93	0
F50A	4N	1303.3	165.9	1.6	1900	3	56.31	0
F50B	4N	602.5	211	2.9	1900	3	55.95	0
F50C	4N	438.2	159.1	1.1	1900	3	67.98	0
F50D	4P	686	112.3	0.3	1900	3	77.14	0
F50E	4N	486	245.8	5.1	1900	3	51.55	0
F50F	4N	574.2	132.7	0.5	1900	3	72.86	0
F50G	4P	773.5	96	0.1	1900	3	83.33	0
F60A	4P	570.5	103	0.2	1800	3	82.62	0
F60B	4P	319.4	129.2	0.6	1800	3	78.57	0
F60C	4P	621	113.7	0.3	1800	3	78.21	0
F60D	4P	480.1	120	0.4	1800	3	78.21	0
F60E	4P	793.3	116	0.4	1800	3	76.31	0
G10A	4A	171.8	1580.2	1014.5	1475	1	0	375.7
G10B	4A	126	1245.1	726.2	1515	1	0	259.26
G10C	4E	328.1	1009.2	447.6	1500	1	0	141.9
G10D	4E	687.5	625.4	168	1595	1	0	53.75
G10E	4E	394.1	640	173.4	1635	1	0	55.21
G10F	4E	539.4	514.7	112.8	1615	1	0	36.18
G10G	4E	185.6	912.3	668.3	1640	1	0.24	207.4
G10H	4G	674.5	411.3	31.4	1615	2	0.6	9.36
G10J	4G	867.5	447	40.2	1605	2	0.12	12.11
G10K	4T	1175.9	381.9	21.4	1520	3	28.69	2.14
G10L	4T	1754.5	390	28.8	1485	3	28.93	2.83
G10M	4T	2004.7	300.3	8.7	1460	3	34.64	0.56
G21A	4T	523.3	407.8	31.7	1450	3	33.33	2.28
G21B	4T	303.8	423.6	31.6	1445	3	34.29	2.09
G21C	4G	244.2	522.9	62.3	1560	2	0.36	18.85
G21D	4G	484	476.5	48.6	1490	2	0	14.84
G21E	4G	530.8	530.6	68.4	1485	2	0	20.89
G21F	4G	242.4	488.4	54.1	1430	2	0	16.84
G22A	4G	238	683.7	132.8	1400	1	0	41
G22B	4G	109.4	922.6	296.3	1400	1	0	87.9
G22C	4G	254.2	605.4	91.7	1400	1	0	28.73
G22D	4G	246	737.9	165.4	1400	1	0	50.13
G22E	4G	270.7	571.6	76.8	1410	1	0	24.2
G22F	4A	65.7	1464.5	868.2	1450	1	0	342.63
G22G	4G	106.4	753.6	154.7	1455	1	0	47.49
G22H	4G	227.3	669.2	110.6	1415	1	0	35.04
G22J	4A	128.2	1002.1	459.4	1410	1	0	174.55
G22K	4A	79.8	769.1	300	1400	1	0	113.64
G30A	4T	761.3	259.7	6.3	1495	3	43.45	0.07
G30B	4G	658.4	393.6	28.7	1615	2	0.6	8.68
G30C	4G	351.2	409.5	32.2	1615	2	2.26	9.32
G30D	4T	534.4	384.3	22.3	1570	2	32.5	1.72
G30E	4T	352	248.6	5.4	1510	3	52.26	0
G30F	4T	779.9	285.2	8.7	1600	3	40.6	0.25
G30G	4T	647.2	253	5.4	1600	3	52.62	0
G30H	4T	1077.2	214	3.1	1625	3	49.76	0
G40A	4A	71.5	1120.5	537.5	1405	1	0	215.07
G40B	4A	122.4	936.6	403.3	1410	1	0	157.19
G40C	4A	144.6	1367.1	728.3	1410	1	0	296.58
G40D	4A	327.2	983.8	435.5	1418	1	0	171.36
G40E	4J	277.6	721.8	134.9	1415	2	0.36	40.73
G40F	4J	422.5	515.3	51.4	1400	2	0.24	16.43
G40G	4J	220.5	723.8	135.9	1415	2	0.48	41.1
G40H	4J	95.9	697.8	121.9	1410	2	3.1	35.45
G40J	4J	168.5	613.4	86.4	1440	2	2.02	25.96
G40K	4J	429.1	495.8	45	1430	2	0.48	14.23
G40L	4J	385.1	569	55.8	1440	2	0	18.64
G40M	4J	393.1	573.5	57.5	1440	2	0	19.01
G50A	4G	242.5	545	0	1440	2	0.48	0
G50B	4J	339.3	531.1	45.1	1445	2	0.12	15.01
G50C	4J	421.4	488.8	34.9	1440	2	0.12	11.71
G50D	4J	572.4	431.4	27.1	1465	5	0.24	9.13
G50E	4J	313.2	448.4	30.4	1465	5	1.31	10.05
G50F	4J	290.4	453.1	27.2	1440	5	0.95	9.16
G50G	4J	380.1	371.4	17.4	1430	5	1.55	5.6
G50H	4M	889.7	370.5	17.2	1470	5	0.24	5.71
G50J	4M	516.5	364.6	16.6	1430	5	1.31	5.45
G50K	4M	162.8	440.6	25.8	1420	5	1.9	8.69
H10A	4E	233.7	512.4	167.9	1670	1	1.07	50.43
H10B	4E	162.5	707.8	287.7	1650	1	0.6	87.98
H10C	4E	259.6	673.6	266.2	1650	1	0.36	81.97
H10D	4E	97	1018.9	519.6	1640	1	0.6	162.69
H10E	4E	84.8	1403.8	1063.5	1605	1	0	374.8
H10F	4E	247.9	783.7	349.2	1625	1	0.12	109.06
H10G	4E	270.4	787.8	353.3	1610	1	0.12	110.68

H10J	4E	213.8	1594.9	858.9	1570	1	0	302.19
H10K	4E	193.5	1224.8	573.2	1545	1	0	202.15
H10L	4R	95.8	476.2	93.8	1605	2	29.05	9.17
H20A	4V	140.5	357.1	33.6	1680	2	47.86	0
H20B	4Q	124.4	590.3	33.1	1660	2	3.1	9.54
H20C	4Q	80.6	643	44.4	1675	2	4.64	12.68
H20D	4E	100.7	696	277.2	1660	1	2.02	86.52
H20E	4E	95.2	906.4	423.2	1645	1	1.43	136
H20F	4Q	116.6	796.9	96.6	1660	2	0.95	28.74
H20G	4Q	85.1	680.1	55.3	1640	2	3.21	15.61
H20H	4R	89	299.6	29.2	1620	2	43.81	0.27
H30A	4R	284.2	442.6	57.4	1530	3	26.43	6.51
H30B	4R	315	374.4	34.9	1600	3	33.1	2.56
H30C	4R	327.1	479.5	71.3	1650	3	22.86	9.62
H30D	4R	127.1	385.1	37.8	1615	3	37.14	1.86
H30E	4R	153.8	440.9	57.8	1550	3	17.62	10.29
H40A	4V	184.4	426.2	35.3	1660	2	33.57	2.49
H40B	4Q	240.5	577.5	15.4	1645	2	0	6.28
H40C	4R	271.8	374.9	52.2	1620	3	30.48	4.65
H40D	4R	181.8	556.7	136.3	1500	3	23.21	18.09
H40E	4R	285.4	539.1	126.3	1545	3	22.5	17.3
H40F	4R	339.9	292.8	26.8	1560	3	36.07	1.49
H40G	4R	263.4	417	66	1495	3	14.17	12.81
H40H	4R	207.9	460.8	87.5	1605	3	26.67	9.8
H40J	4R	203.6	417	52	1560	3	17.5	9.13
H40K	4R	270.6	405.7	46.1	1490	3	17.38	8.01
H40L	4R	158.9	381.3	38.4	1555	3	22.38	5.53
H50A	4R	264.5	335.3	26	1480	4	23.33	3.55
H50B	4R	430.6	389.2	38.7	1485	4	17.38	6.58
H60A	4E	72.6	1894.5	1206.8	1440	1	0	416.16
H60B	4E	210	1126.7	563.8	1465	1	0	187.64
H60C	4E	216.9	891	386.2	1470	1	0	128.49
H60D	4J	226.8	651.8	183.7	1450	2	0.24	58.77
H60E	4J	170.5	639.7	174.1	1455	2	0.48	55.33
H60F	4J	164.9	581.6	141.2	1450	5	0.83	44.08
H60G	4J	141.2	475.2	83	1420	5	0.83	27.14
H60H	4J	253	464	77.9	1420	5	0.36	25.65
H60J	4J	293.1	457.4	75.1	1415	5	0.24	24.85
H60K	4M	262.2	371.2	44.3	1410	5	1.67	13.95
H60L	4M	230.3	360.8	41.3	1405	5	2.14	13.06
H70A	4M	223.8	414.4	58.9	1415	5	1.55	18.96
H70B	4C	153.1	694.4	269.3	1450	7	0	147.65
H70C	4W	287.4	372.5	48.8	1520	4	35.36	2.92
H70D	4C	170.4	634.8	229.4	1440	7	0	123.07
H70E	4C	156.8	741	303.2	1445	7	0	166.66
H70F	4C	120.8	573.2	189.3	1440	7	0	100.67
H70G	4M	651.9	365.8	14.9	1420	5	0.12	5.42
H70H	4M	400.1	395.4	18.5	1440	5	0.48	6.6
H70J	4M	551	383.2	17.1	1400	5	0.12	6.27
H70K	4M	207.3	458.4	29	1410	5	0.83	10.08
H80A	4C	149	597	208.7	1440	7	0	106.92
H80B	4C	123	791.7	345.5	1440	7	0	184.35
H80C	4M	284.8	479.4	28.8	1400	5	0	11.34
H80D	4M	230.7	412.7	22.1	1400	5	0.71	8.05
H80E	4M	373.4	430.8	25.2	1400	5	0	9.26
H80F	4M	203.6	533	46.6	1400	5	0	16.66
H90A	4C	179.1	644.7	230.7	1400	7	0	117.91
H90B	4C	118.2	663.8	243.2	1400	7	0	125.05
H90C	4M	217.6	466.7	25.7	1400	5	0	10.05
H90D	4M	602.1	425.1	23.1	1400	5	0	8.6
H90E	4M	495.7	489.6	34.9	1400	5	0	12.79
J11A	4Y	437.6	295.3	15.3	1965	4	32.62	1.17
J11B	4Y	737.8	252.1	9.5	2040	4	35.12	0.58
J11C	4Y	292.2	204.1	4.8	2110	4	49.76	0
J11D	4Y	801.2	240.5	8.1	2000	4	35.6	0.47
J11E	4Y	812.2	188	4.9	2060	4	49.64	0
J11F	4Y	344.4	209.1	7	2110	4	51.19	0
J11G	4Y	604.3	166.4	3.3	2140	4	56.31	0
J11H	4W	651.4	239.6	3.7	2080	4	29.29	0.36
J11J	4W	449.8	303.7	8.4	1915	4	26.31	0.96
J11K	4W	515.9	220.6	3.1	1830	4	36.55	0.16
J12A	4V	180.8	437	37.6	1690	3	27.26	4.08
J12B	4V	251	268.2	9.6	1700	3	38.81	0.38
J12C	4V	366	287.4	11.5	1800	3	33.93	0.79
J12D	4V	830.8	289.3	11.6	1720	3	26.9	1.28
J12E	4W	355.7	306.6	8.1	1880	4	26.07	0.94
J12F	4W	709.9	245.3	6.3	1750	4	32.5	0.49
J12G	4W	760.9	276.7	5.9	1960	4	22.98	0.86
J12H	4W	549.4	259.5	7.8	1840	4	32.74	0.59
J12J	4W	548.9	250	5.3	1610	4	31.55	0.44
J12K	4W	516.6	192.5	3.1	1740	4	42.62	0.05

J12M	4W	483	289.9	7.2	1550	4	27.02	0.79
J13A	4W	518	295.2	7.5	1650	4	24.52	1.05
J13B	4W	401.8	305.7	8.5	1580	4	25.24	1.02
J13C	4W	435.1	350.5	13.1	1540	4	20.48	2.05
J21A	4Z	854.4	229.9	17.3	2300	4	26.19	1.99
J21B	4Z	530.3	187.8	9.6	2305	4	36.55	0.51
J21C	4Z	526.1	165.6	8.4	2350	4	45.95	0
J21D	4Z	649.6	154.9	6.9	2305	4	46.31	0
J21E	4Z	504.4	153.9	6.5	2325	4	45.95	0
J22A	4Z	436.1	233	23.9	2130	4	36.31	1.29
J22B	4Z	321.6	205.2	16.8	2040	4	40.71	0.47
J22C	4Z	364.3	196.5	15.1	2110	4	41.07	0.39
J22D	4Z	680.4	161.6	8.5	2110	4	42.62	0.14
J22E	4Z	833.9	158.6	8.2	2090	4	41.43	0.19
J22F	4Z	295.9	118.1	37.1	2230	4	28.21	3.81
J22G	4Z	566.8	220.8	15.5	2150	4	30.36	1.39
J22H	4Z	807.3	229.9	17.3	2200	4	26.67	1.94
J22J	4Z	377.6	187.2	11.6	2180	4	44.64	0.05
J22K	4Z	479.1	150.8	6.5	2250	4	48.81	0
J23A	4Z	762.1	126.6	3.7	2295	4	49.29	0
J23B	4Z	782.2	146.8	5.8	2305	4	44.52	0.03
J23C	4Z	514.3	123.8	2.3	2250	4	49.64	0
J23D	4Z	707.7	178.4	2	2185	4	50.83	0
J23E	4P	225.1	329	32.9	2120	4	5.36	9.2
J23F	4Z	477.6	194.2	9.2	2180	4	34.05	0.62
J23G	4Z	240.6	97.7	1.2	22250	4	67.86	0
J23H	4Z	264.2	199.4	9.8	2150	4	38.21	0.42
J23J	4P	228.6	307.7	28.8	2105	4	5.83	8.14
J24A	4Z	926	202.9	17.6	2225	4	36.07	0.98
J24B	4Z	767.7	160.3	8.9	2250	4	43.81	0.08
J24C	4Z	861.3	145.5	4.5	2305	4	43.1	0.06
J24D	4Z	926.1	127.5	2.9	2310	4	46.43	0
J24E	4Z	862.2	133.9	3.4	2280	4	45.48	0
J24F	4W	282.4	221.7	2.8	2220	4	44.4	0.02
J25A	4P	353.6	288.6	24.6	2040	4	4.76	7.04
J25B	4P	396.9	325.6	34.3	1950	4	3.45	10.35
J25C	4W	180.6	288.1	6.1	1825	4	36.31	0.33
J25D	4P	210.4	365.2	45.7	1945	4	4.52	13.35
J25E	4W	286.5	244.5	3.5	1800	4	38.21	0.15
J31A	4U	446.8	441	21.5	1780	4	1.07	6.92
J31B	4U	200.5	359.2	11.5	1770	4	6.07	3.5
J31C	4U	167.9	369.2	11.9	1890	4	8.21	3.61
J31D	4U	303.6	300	6.6	1840	4	6.67	2.06
J32A	4Z	415.2	153.9	1.4	2250	4	63.45	0
J32B	4Z	642.8	159.8	1.6	2130	4	57.98	0
J32C	4Z	734.5	135.5	1	2215	4	63.33	0
J32D	4Z	301.7	160.2	1.7	2150	4	65.83	0
J32E	4Z	971	234.3	5.3	1990	4	46.19	0
J33A	4P	449.4	392.5	11.4	18353	6	2.62	4.01
J33B	4P	590.8	436.9	15.6	1830	6	1.19	5.51
J33C	4Z	428.1	292.9	6.1	2070	6	34.17	0.41
J33D	4P	258.9	379	47.9	1980	6	3.93	14.25
J33E	4P	328.8	445.7	74.8	1860	6	2.86	23.04
J33F	4P	365.8	343.3	32	1840	6	2.38	10.9
J34A	4N	252.1	476.5	22.2	1660	6	2.74	7.25
J34B	4N	341.5	569.3	37.7	1665	6	1.07	12.3
J34C	4N	318.9	673.5	66.8	1605	6	0.36	21.66
J34D	4N	354.3	470.8	21.8	1620	6	0.12	7.74
J34E	4N	258.1	426.7	16.7	1540	6	1.43	5.98
J34F	4N	320.1	415	14.7	1620	6	1.43	5.42
J35A	4P	427.5	418.3	53	1940	4	1.79	17.78
J35B	4N	651.4	410.5	14.4	1590	6	0.12	5.29
J35C	4N	264.6	373	10.6	1580	6	2.5	3.98
J35D	4P	507.2	406.5	49.9	1900	4	1.67	17.04
J35E	4P	215.3	269.9	20	1780	4	5.71	5.83
J35F	4P	500.4	341.3	36.6	1820	4	2.38	11.62
J40A	4K	453.6	417.9	70.3	1600	5	1.9	22.44
J40B	4K	222	431.1	77.5	1450	5	2.26	24.99
J40C	4K	436.3	521.3	89.7	1400	5	0	34.05
J40D	4K	655	445.6	38.9	1400	5	0	13.92
J40E	4K	554.2	440.1	37.5	1400	5	0.12	13.39
K10A	4K	177.5	450.3	34.3	1400	5	0.48	12.95
K10B	4K	171.2	446.3	33.3	1400	5	0.48	12.32
K10C	4K	159	492.7	70.4	1400	5	0.12	27.46
K10D	4K	164	454.1	34.8	1400	5	0.48	12.87
K10E	4D	132.6	679.3	236.8	1400	7	0	113.4
K10F	4K	105.8	502.4	46.2	1400	5	0.71	17.03
K20A	4D	168.5	722	239.3	1400	7	0	123.77
K30A	4D	196	752.8	267.9	1400	7	0	140.92
K30B	4D	138.6	787.2	300	1400	7	0	159.88
K30C	4D	190.1	805.1	284.2	1400	7	0	147.87

K40A	4D	87.5	705.6	213.8	1400	7	0	111.24
K40B	4D	111.6	845.6	239.3	1400	7	0	124.44
K40C	4D	99.6	930.4	339	1400	7	0	192.9
K40D	4D	129.8	756.7	253.8	1400	7	0	142.22
K40E	4D	267.6	864.3	198.5	2100	7	0	94.19
K50A	4D	235.4	849.6	228.9	1400	7	0	115.1
K50B	4D	202.9	881.9	238.9	1400	7	0	130.02
K60A	4D	161.4	663.9	86.3	1540	7	0	42.03
K60B	4D	143.2	753.6	121.7	1500	7	0	66.24
K60C	4D	160.8	744.4	124.8	1400	7	0	69.39
K60D	4D	292.5	814.6	152.4	1400	7	0	84.86
K60E	4D	100.2	774.5	101	1400	7	0	57.69
K60F	4D	242.1	806.5	97.5	1400	7	0	53.61
K60G	4D	166.6	860	114.4	1400	7	0	66.98
K70A	4D	170.3	920.1	151.8	1400	7	0	80.73
K70B	4B	106.4	997.2	381.1	1400	7	0	210.73
K80A	4B	145.9	1029.5	480.1	1400	7	0	287.43
K80B	4B	208.2	1031.1	454.8	1400	7	0	272.29
K80C	4B	188.8	1016.8	419	1400	7	0	239
K80D	4B	173	936.2	381.3	1400	7	0	211.02
K80E	4F	265.8	894.7	203.8	1400	7	0	86.51
K80F	4F	220.9	545.7	153.8	1400	7	0	66.71
K90A	4F	213.5	716.2	142.1	1400	6	0	57.87
K90B	4F	149.6	774.1	170.7	1400	6	0	69.38
K90C	4H	267	596.3	50.9	1450	6	0	21.41
K90D	4H	215.2	692.6	79.5	1400	6	0	32.94
K90E	4H	176.4	676.2	68.2	1400	6	0	30.08
K90F	4H	250.3	698.5	75.2	1400	6	0	32.62
K90G	4H	286.5	653.8	59.8	1460	6	0	26.01
L11A	4Z	930.1	218.3	5.8	2150	4	35.95	0.33
L11B	4Z	875	234.5	7.3	2155	4	34.05	0.49
L11C	4Z	568.2	241.1	7.9	2180	4	36.67	0.41
L11D	4Z	1286.4	224.4	6.3	2185	4	32.74	0.48
L11E	4Z	455.7	227	6.4	2250	4	41.79	0.14
L11F	4Z	745	219.8	5.8	2280	4	38.81	0.23
L11G	4Z	2024.4	195.4	3	2300	4	42.98	0.04
L12A	4Z	905.6	159.4	2.6	2310	4	53.81	0
L12B	4Z	518.7	192.2	4.8	2300	4	52.02	0
L12C	4Z	1067.6	151.6	2.3	2255	4	54.17	0
L12D	4Z	869.9	169.6	3.4	2220	4	51.43	0
L21A	4Z	609.3	243.9	8.5	2135	4	36.79	0.44
L21B	4Z	756.3	249.7	9.3	2105	4	34.76	0.59
L21C	4S	1033.5	300	10.7	2040	4	21.79	1.51
L21D	4S	864.6	366.6	19.9	2000	4	17.74	3.29
L21E	4S	712.3	289.4	9.6	2050	4	25.6	1.14
L21F	4Z	576.1	251	9.4	2115	4	36.43	0.5
L22A	4Z	1072.4	227.2	7.8	2160	4	34.29	0.52
L22B	4Z	474.6	209.6	4.8	2185	4	50.71	0
L22C	4Z	759.6	234.4	7	2100	4	43.1	0.09
L22D	4Z	530.4	275.7	11.5	2050	4	40.36	0.34
L23A	4Z	516	178.5	4.8	2200	4	53.69	0
L23B	4Z	818.1	235.2	10.6	2080	4	40.83	0.29
L23C	4Z	890.6	183.4	5.2	2130	4	49.05	0
L23D	4Z	664.6	187	5.6	2110	4	49.88	0
L30A	4Z	360.8	283.9	8.3	1980	4	45.71	0
L30B	4Z	378	221.3	7.7	2125	4	48.81	0
L30C	4Z	237.2	244.8	10.5	2100	4	49.17	0
L30D	4Z	551.7	248.5	5.4	1975	4	48.1	0
L40A	4Z	762.6	216	4.6	1985	4	45	0.01
L40B	4Z	593.8	240.6	6.6	1975	4	43.1	0.09
L50A	4Z	466.4	294.7	9.4	1860	4	41.43	0.22
L50B	4Z	556.9	268	6.8	1885	4	44.4	0.04
L60A	4Z	677.2	233.8	5.9	1920	4	43.1	0.08
L60B	4Z	671	218.3	4.8	1860	4	45.71	0
L70A	4Z	581.5	248.5	5.3	1790	4	47.62	0
L70B	4Z	440.6	236.3	3	1760	4	55.36	0
L70C	4Z	661.8	224.2	4	1740	4	47.74	0
L70D	4Z	535.8	252.5	5	1735	4	46.07	0
L70E	4Z	701.7	282.9	7.4	1720	4	39.4	0.26
L70F	4Z	306.4	316	10.8	1670	4	42.5	0.18
L70G	4H	469.7	503.9	30.9	1640	6	0	13.07
L81A	4U	332.1	526.8	53.3	1740	6	1.19	17.16
L81B	4U	261.1	427.8	32.2	1715	6	2.14	10.46
L81C	4U	332.1	436.7	34.3	1670	6	1.43	11.16
L81D	4U	307.7	393	26.6	1640	6	1.55	8.79
L82A	4N	269.2	595.1	55.8	1620	6	0.12	19.96
L82B	4N	404.7	677.7	77.8	1630	6	0.12	27.71
L82C	4N	362.1	685.8	79	1570	6	0.12	28.39
L82D	4N	590.8	577.9	53	1550	6	0	20
L82E	4N	365	584.5	50.7	1530	6	0	19.21
L82F	4N	168.6	511.8	33.7	1540	6	0.36	13.56

L82H	4N	229.9	450.5	23	1620	6	0.36	9.11
L82J	4N	164	491	30.5	1530	6	0.36	12.31
L90A	4H	515.9	541.6	38.6	1580	6	0	16.38
L90B	4H	365.8	596.7	103	1550	6	0	37.13
L90C	4H	318.9	607.4	107.5	1530	6	0	38.66
M10A	5Q	264.3	533.2	60.4	1600	8	1.31	20.16
M10B	5Q	392.9	557.5	67.4	1600	8	0.95	22.14
M10C	5Q	429.9	564.6	71.1	1550	8	0.95	23.93
M10D	5X	306.5	470.6	18.3	1550	8	44.29	0.12
M20A	5V	361.5	659.5	56.2	1500	8	21.43	8.06
M20B	5Q	307.5	724.9	134.6	1500	8	0.12	45.23
M30A	5X	257.8	451.2	19.6	1600	8	50.83	0
M30B	5X	306.6	434.4	17.3	1550	8	52.14	0
N11A	5T	699.9	361.6	13.2	1850	4	16.43	2.31
N11B	5T	774.1	332.6	10.3	1900	4	17.38	1.76
N12A	5T	737.6	362.6	12.9	1900	4	16.07	2.4
N12B	5T	799.7	348.1	11.4	1950	4	16.43	2.11
N12C	5T	656.4	354.1	12	1900	4	16.9	2.08
N13A	5T	553.8	381.3	15.5	1950	4	15.95	2.77
N13B	5T	482.1	377.5	15.1	1950	4	17.5	2.58
N13C	5T	491.3	306.9	7.9	1900	4	22.62	1.19
N14A	5U	505.1	260.9	9.6	2000	8	25.24	1.16
N14B	5U	388.7	266.4	10.1	1950	8	27.74	1.07
N14C	5U	655.2	390.3	29.7	2000	8	15.71	5.3
N14D	5U	366.4	289.7	13	1950	8	25.24	1.57
N21A	5T	457.4	272.6	8.3	1900	8	21.9	1.29
N21B	5T	387.7	411.4	28.3	1850	8	12.26	5.84
N21C	5T	751.1	316	13	1850	8	13.57	2.61
N21D	5T	559.7	287.8	9.8	1850	8	17.98	1.69
N22A	5U	606.7	276.9	12.4	1800	4	22.14	1.77
N22B	5U	642.5	216.8	5.8	1800	4	28.45	0.59
N22C	5U	398.7	254.2	9.5	1800	4	28.45	0.96
N22D	5U	344	302.9	16.2	1800	4	25.48	1.93
N22E	5U	342.3	239.9	8	1750	4	31.31	0.67
N23A	5U	537.1	318.4	16.4	1700	4	17.86	2.73
N23B	5U	245.3	276.8	10.8	1700	4	28.69	1.08
N24A	5U	665.8	246.3	8.7	1950	4	24.88	1.13
N24B	5U	665.7	246.9	8.8	1850	4	24.88	1.14
N24C	5U	797.4	251.6	9.3	1850	4	23.21	1.27
N24D	5U	383.9	214.5	5.7	1850	4	35.24	0.35
N30A	5T	848.9	386.9	24.3	1800	4	8.33	5.61
N30B	5T	736.6	316.5	13.3	1800	4	13.1	2.7
N30C	5T	346.3	315	13.2	1750	4	19.17	2.22
N40A	5R	667.7	352.8	9.7	1700	4	4.64	2.95
N40B	5X	1209.6	318.5	6.8	1650	4	59.05	0
N40C	5R	579.9	504.5	23.2	1650	4	0.83	7.54
N40D	5X	668.7	473.7	20.3	1600	4	40.71	0.56
N40E	5X	510.1	363.6	7.8	1600	4	58.81	0
N40F	5X	762.1	481.6	21.8	1550	4	39.17	0.81
P10A	5R	125.5	599.9	35.8	1550	8	1.19	11.31
P10B	5R	508.3	531.4	24.1	1550	8	0.24	8.07
P10C	5R	280.7	386.4	8.5	1650	8	3.93	2.99
P10D	5R	563.9	432	12.4	1600	8	0.71	4.48
P10E	5V	466.3	493.5	18.7	1550	8	38.69	0.75
P10F	5V	469.1	557.1	29.2	1550	8	32.74	2.21
P10G	5V	343.2	549.8	28.5	1500	8	34.88	1.79
P20A	5V	421.8	714.9	71.7	1500	8	17.14	12.13
P20B	5V	331.7	634.9	46.5	1550	8	26.9	5.14
P30A	5R	175.8	623.4	39.5	1500	8	0.95	12.72
P30B	5V	402.7	559.1	29	1500	8	32.14	2.3
P30C	5V	67.6	535.5	24.9	1500	8	49.76	0
P40A	5R	311.6	635.2	43.5	1500	8	0.36	14.23
P40B	5V	264.3	570	31	1500	8	34.4	2.03
P40C	5V	342.1	616.2	41.5	1450	8	28.45	4.2
P40D	5V	245.7	665.5	54.3	1450	8	26.19	6.24
Q11A	5T	382.2	395.8	19.6	1800	8	24.52	2.52
Q11B	5T	375.5	351.9	13.8	1800	8	27.14	1.51
Q11C	5T	361.6	348.4	13.3	1800	8	27.86	1.39
Q11D	5T	481.2	316.3	10	1800	8	27.86	1.05
Q12A	5T	626.9	383.5	16.3	1750	8	19.64	2.52
Q12B	5T	637.1	407	19.5	1750	8	18.21	3.17
Q12C	5T	428.1	342.7	11.5	1800	8	24.05	1.58
Q13A	5T	1031	327.3	10.4	1800	8	17.98	1.71
Q13B	5T	240	288.7	7.1	1800	8	35.12	0.44
Q13C	5T	454.3	304.8	8.4	1800	8	27.14	0.92
Q14A	5T	486	348.2	13.6	1850	8	27.02	1.49
Q14B	5T	725.3	345.1	13.3	1850	8	23.33	1.77
Q14C	5T	834.8	319.6	10.6	1850	8	24.05	1.37
Q14D	5T	408.3	290.3	7.9	1800	8	32.38	0.61
Q14E	5T	342.8	306.7	9.4	1850	8	32.38	0.73
Q21A	5T	600.2	353.9	12.9	1850	8	22.14	1.84

Q22A	5T	518	348.3	12.3	1850	8	23.69	1.67
Q22B	5T	219.7	328.2	10.3	1850	8	32.5	0.79
Q30A	5P	394.4	390.1	17.7	1850	8	0.71	6.39
Q30B	5T	481.9	339.2	10.1	1850	8	22.62	1.48
Q30C	5T	420.4	327.8	9.1	1800	8	24.17	1.29
Q30D	5T	310.9	343.8	10.5	1800	8	25.83	1.23
Q30E	5T	325.8	347	10.8	1800	8	25	1.5
Q41A	5T	229.6	537.3	33.3	1700	8	12.98	6.96
Q41B	5T	433.9	448.9	19.3	1700	8	12.26	4.08
Q41C	5T	333.1	432.7	17.3	1700	8	15.12	3.26
Q41D	5T	295.2	360	9.8	1750	8	21.55	1.62
Q42A	5T	445.5	454	21.5	1750	8	15.36	4.09
Q42B	5T	375.6	423.3	17.3	1750	8	18.1	2.92
Q43A	5T	705.5	390.6	13.6	1750	8	15.36	2.59
Q43B	5T	802.6	341.5	9	1750	8	17.74	1.53
Q44A	5T	425.4	353.5	11	1750	8	20.6	1.75
Q44B	5T	448.9	319.3	8.1	1800	8	22.74	1.23
Q44C	5T	254.2	342.3	10	1750	8	25.71	1.18
Q50A	5T	639.6	373	11.9	1750	8	13.69	2.44
Q50B	5T	402.9	409.8	15.9	1750	8	14.4	3.26
Q50C	5T	197.9	412.4	16.3	1700	8	20.83	2.71
Q60A	5T	315.6	499.3	25.4	1700	8	10.95	5.88
Q60B	5T	369.4	505.7	26.6	1700	8	9.52	6.22
Q60C	5T	131.5	448.5	18.3	1700	8	19.88	3.32
Q70A	5T	251.2	427.4	18.5	1700	8	18.33	3.2
Q70B	5T	457.7	374.8	12.3	1700	8	16.31	2.23
Q70C	5T	249.5	362.9	11.2	1650	8	21.79	1.85
Q80A	5P	356.5	420.7	19.6	1800	8	0.71	7.33
Q80B	5P	449.6	407	17.8	1800	8	0.6	6.61
Q80C	5P	281.2	414.9	18.9	1800	8	1.07	7.08
Q80D	5P	417.8	493.4	30.8	1750	8	0.48	10.8
Q80E	5T	364.4	376.1	15.5	1700	8	18.45	2.62
Q80F	5T	700.9	355	12.9	1700	8	16.07	2.29
Q80G	5T	266.3	358.4	13.4	1650	8	22.74	2.04
Q91A	5T	477.5	397.1	15.4	1600	8	12.02	3.32
Q91B	5T	514.6	451.3	22.7	1600	8	8.81	5.31
Q91C	5W	485	490.7	16.8	1550	8	42.14	0.32
Q92A	5K	324	661.7	67.1	1650	9	0.24	28.57
Q92B	5P	324.4	586.3	35.8	1650	9	0.6	12.6
Q92C	5P	600.6	559.2	30.6	1650	9	0.6	11.07
Q92D	5P	248.7	594.3	38.3	1600	9	0.6	13.54
Q92E	5W	287	463.5	9.4	1600	8	48.57	0
Q92F	5W	665.3	414.7	6	1650	8	49.76	0
Q92G	5W	884.4	465.8	9.6	1600	8	41.31	0.23
Q93A	5W	336.6	445.4	12.9	1500	8	48.93	0
Q93B	5W	392.2	470.2	15.8	1500	8	44.29	0.1
Q93C	5W	413.5	475.9	16.7	1450	8	44.05	0.13
Q93D	5V	490.8	560.5	35.5	1450	8	32.74	2.68
Q94A	5K	258.9	803.9	92.5	1550	10	0	39.84
Q94B	5K	147.4	705.7	71.7	1600	10	0.12	29.71
Q94C	5K	135.2	768.1	91.2	1600	10	0	36.54
Q94D	5P	212	607.3	35.7	1550	9	0.48	13.09
Q94E	5P	227.7	641	42.1	1600	9	0.48	14.5
Q94F	5W	734.1	481.8	11.2	1550	8	40.48	0.33
R10A	5K	137.8	835	105	1500	10	0	44.46
R10B	5K	222.2	860.6	114.3	1500	10	0	47.34
R10C	5K	125.5	787.9	89.3	1500	10	0	38.42
R10D	5K	178.4	709.9	66.6	1500	10	0	29.52
R10E	5S	198.2	545.9	30.9	1500	9	1.31	10.6
R10F	5K	70.7	1036.2	183.1	1550	10	0.12	72.04
R10G	5K	168.9	618.7	43.9	1550	10	0	20
R10H	5S	243.3	518.1	25.4	1550	9	1.31	8.69
R10J	5S	178.8	451.7	16.9	1500	9	3.57	6.08
R10K	5S	602.7	519.3	27.1	1450	9	0.24	9.62
R10L	5S	394.7	521.3	38.1	1400	9	0.48	12.42
R10M	5S	176.5	618.6	63.7	1400	9	0.6	20.1
R20A	5K	139.4	1010.7	179.3	1450	10	0	70.88
R20B	5K	154.7	695.6	64.7	1450	10	0	29.12
R20C	5K	121	800.2	94.8	1450	10	0	40.42
R20D	5S	258.3	574.4	39.6	1450	9	0.36	13.46
R20E	5S	249.4	657.3	61.5	1400	9	0.24	20.76
R20F	5S	260.9	675.4	84.1	1400	9	0.36	26.09
R20G	5S	103.2	812	141.9	1350	9	0.71	43.71
R30A	5S	425.5	866.2	130.8	1300	9	0	43.06
R30B	5S	527	793.4	97.5	1350	9	0	32.46
R30C	5S	507.1	687.8	61.4	1400	9	0	20.93
R30D	5S	150.6	785.1	94.6	1350	9	0.12	31.37
R30E	5S	471.6	670.5	72	1400	9	0	23.32
R30F	5S	208.6	793.4	119.3	1350	9	0.12	37.77
R40A	5S	332.5	765.4	121.2	1350	9	0.24	37.41
R40B	5S	326.1	609.1	63.3	1400	9	0.48	19.79

R50A	5S	393.8	579.4	52	1400	9	0.48	16.73
R50B	5S	412.7	580.7	52.6	1400	9	0.48	16.95
S10A	5L	257.7	527.6	23.2	1650	9	0.6	8.11
S10B	5L	398.7	579.3	31.2	1350	9	0.36	10.61
S10C	5L	236.4	545.6	25.8	1650	9	0.6	8.97
S10D	5L	316.8	593.7	31.1	1650	9	0.48	10.64
S10E	5L	240.4	588.5	30.6	1600	9	0.48	10.57
S10F	5L	301	584.1	32.1	1650	9	0.36	10.76
S10G	5L	377.3	621.3	36.3	1600	9	0.36	12.32
S10H	5N	473	571.5	38.2	1600	9	0.36	13.38
S10J	5N	324.1	565.5	38.5	1550	9	0.48	13.34
S20A	5J	298.1	627	38.3	1600	9	0	17.85
S20B	5J	446.8	623.5	37.5	1600	9	0	17.65
S20C	5J	552.1	634.2	39.6	1600	9	0	18.33
S20D	5J	309.6	682	50.7	1550	9	0	22.84
S31A	5L	408.9	516.8	20.4	1700	9	0.6	7.48
S31B	5L	400.1	513.3	19.9	1700	9	0.6	7.18
S31C	5L	605.9	485.6	16.7	1700	9	0.48	6.26
S31D	5L	331	555.8	25.6	1650	9	0.6	9.08
S31E	5L	440.5	482	16	1650	9	0.6	5.98
S31F	5L	225.7	562	26.5	1650	9	0.6	9.26
S31G	5L	239.9	507.3	18.5	1650	9	0.71	6.65
S32A	5N	324.3	546.6	25.5	1650	9	0.6	8.55
S32B	5N	559.4	453.5	12.5	1700	9	0.48	4.06
S32C	5N	525.6	493.6	16.8	1650	9	0.36	5.41
S32D	5E	307.2	703.9	98.2	1550	10	0	46.72
S32E	5E	295.1	641.5	74.2	1600	10	0	36.74
S32F	5N	327.1	550.8	27.4	1600	9	0.6	9.3
S32G	5N	237.9	516.1	21.4	1600	9	0.83	7.41
S32H	5N	344.7	482.9	15.6	1650	9	0.48	5.1
S32J	5N	238.6	554.2	37.4	1600	9	0.24	11.3
S32K	5N	399	528.9	31.4	1600	9	0.24	9.57
S32L	5N	286.8	534.6	32.7	1600	9	0.24	10.13
S32M	5N	406.8	576.8	45.4	1550	9	0.12	13.69
S40A	5N	446.3	553.5	32.9	1550	9	0	10.47
S40B	5N	438.5	551.8	34.3	1500	9	0	11.07
S40C	5N	326.9	581.3	43	1500	9	0.12	13.49
S40D	5N	120.8	647.6	62.9	1500	9	0.6	18.57
S40E	5N	502.3	603.1	55.9	1500	9	0	19.17
S40F	5N	335.5	610	60.9	1450	9	0	20.83
S50A	5H	224	730.1	92.7	1500	9	0	33.58
S50B	5H	333.6	818	124.1	1550	9	0	43.12
S50C	5H	383.4	668.7	65.7	1550	9	0	24.75
S50D	5H	395.5	706.7	78.8	1550	9	0	29.1
S50E	5H	447.9	783	131.9	1500	9	0	41.14
S50F	5N	86.8	699.6	73.2	1500	9	0	24.42
S50G	5N	501.2	676.6	69.8	1450	9	0	23.91
S50H	5N	374.8	634.8	52.4	1500	9	0	18.56
S50J	5N	685.1	668	66.7	1450	9	0	22.91
S60A	5D	327.5	818.5	156.6	1500	10	0	80.37
S60B	5D	264	621.7	85.5	1450	10	0	51.16
S60C	5E	215.8	668.5	80.3	1500	10	0	33.12
S60D	5E	265.3	608.5	64.3	1450	10	0	28.35
S60E	5N	214.7	648.7	73.8	1400	10	0	25.26
S70A	5N	339.1	687.1	90.7	1400	12	0	31.26
S70B	5M	267.3	740.9	63.9	1350	12	0	27.83
S70C	5N	197.5	663.5	82.1	1400	9	0	28.85
S70D	5N	513.6	681.8	93.6	1350	9	0	32.3
S70E	5M	480.7	742	64.1	1350	12	0	27.81
S70F	5M	358.6	804.4	90.7	1300	12	0	37.55
T11A	5H	329.7	745	103.6	1500	9	0	35.95
T11B	5H	414.7	746.5	110.6	1450	9	0	38.17
T11C	5H	385.5	856.3	172.4	1400	9	0	57.46
T11D	5H	342.6	848.7	170.7	1400	9	0	56.44
T11E	5H	232.8	938.6	222.3	1400	9	0	71.99
T11F	5H	275.2	897.2	207.1	1350	9	0	67.86
T11G	5H	290.8	746.7	125.7	1350	9	0	42.93
T11H	5H	216.2	721.1	113.2	1350	9	0	39.31
T12A	5H	278.8	845.1	147.4	1500	9	0	49.71
T12B	5H	229.8	739.7	105.4	1450	9	0	37.08
T12C	5H	283.6	741.7	100.3	1500	9	0	35.23
T12D	5H	320.3	724.1	98.5	1450	9	0	34.58
T12E	5H	412.1	724.9	108.1	1400	9	0	37.79
T12F	5H	346.1	745.7	117.6	1400	9	0	40.26
T12G	5H	276.3	683	96.3	1350	9	0	34.08
T13A	5H	287.5	747.2	145.2	1300	12	0	49.74
T13B	5H	285.3	704	124.3	1300	12	0	43.06
T13C	5H	318.3	725.2	134.3	1300	12	0	46.31
T13D	5M	357.3	889.1	127.3	1250	12	0	53.22
T13E	5M	167.5	941.6	166	1200	12	0	67.13
T20A	5C	480.8	940	268	1300	12	0	112.09

T20C	5C	319.7	685.5	137.2	1250	12	0	63.15
T20D	5M	387.6	763.8	74.5	1200	12	0	35.47
T20E	5M	349.4	829.1	98.5	1200	12	0	44.29
T20F	5M	443	763.8	74.5	1200	12	0	35.3
T20G	5M	212.9	958.4	159.3	1200	12	0	65.39
T31A	5G	221.3	907.4	170.1	1350	11	0	55.71
T31B	5G	284	832.6	129.9	1350	11	0	43.65
T31C	5G	290.6	830.4	128.3	1350	11	0	43.32
T31D	5G	352.5	735.9	85.8	1350	11	0	30.7
T31E	5G	508.7	755.6	94	1350	11	0	33
T31F	5G	604.7	713.5	75	1350	11	0	27.86
T31G	5G	208.4	800.6	119.2	1300	11	0	41.25
T31H	5G	616.2	808	122.7	1300	11	0	42.46
T31J	5G	506.4	806.9	97.5	1300	11	0	36.77
T32A	5G	347.1	804.3	90.3	1300	11	0	35.34
T32B	5G	306.5	814.2	103.1	1250	11	0	39.95
T32C	5G	372.9	781	97.4	1200	11	0	38.32
T32D	5G	350.2	788.7	92.2	1250	11	0	36.25
T32E	5G	382	844.1	119.9	1200	11	0	47.67
T32F	5G	296.7	923.9	160.9	1200	11	0	61.01
T32G	5G	437.7	861.8	128.6	1200	11	0	50.77
T32H	5G	452.2	891.7	143.7	1200	11	0	55.2
T33A	5G	671.9	757.3	100.7	1350	11	0	35.02
T33B	5G	601.9	800.5	113.5	1400	11	0	38.5
T33C	5G	366.9	767.7	98.5	1400	11	0	34.21
T33D	5G	461	736.5	91.5	1350	11	0	32.23
T33E	5G	267.1	748.4	91.4	1350	11	0	33.42
T33F	5G	437	828.9	127.5	1350	11	0	44.2
T33G	5G	502.5	835.5	139.5	1300	11	0	48.11
T33H	5G	516	780.3	88.5	1250	11	0	36.26
T33J	5G	456.4	730	76.5	1200	11	0	32.64
T33K	5G	169.1	856.3	131.9	1200	11	0	51.08
T34A	5C	241.5	904.8	208.5	1400	11	0	82.22
T34B	5C	246.1	859.8	184.1	1400	11	0	73.84
T34C	5C	281.9	807.3	156.4	1400	11	0	64.58
T34D	5C	341.4	850.3	188	1350	11	0	75.09
T34E	5C	268.2	900.8	206.2	1400	11	0	81.23
T34F	5C	237.7	874.8	201.5	1350	11	0	79.69
T34G	5C	358	894.5	191.9	1350	11	0	84.12
T34H	5C	590.1	863.1	185.4	1300	11	0	81.88
T34J	5G	296.3	770.8	88.9	1250	11	0	35.74
T34K	5G	332.9	715	74.2	1200	11	0	31.05
T35A	5C	475.1	912	230.5	1400	11	0	92.59
T35B	5C	395.7	914.6	233.1	1400	11	0	93.6
T35C	5C	306.1	916	288.6	1400	11	0	113.28
T35D	5C	347.8	818.1	186.6	1350	11	0	77.32
T35E	5C	491.8	918.3	244.8	1350	11	0	97.81
T35F	5C	358.7	859.5	199.7	1400	11	0	82.16
T35G	5C	574.5	759.2	148.9	1400	11	0	64.18
T35H	5C	519.3	845.1	201.2	1350	11	0	83.18
T35J	5C	188.4	923.9	258	1300	11	0	103.43
T35K	5C	624.8	783	177.8	1300	11	0	77.9
T35L	5G	340.1	763.5	84.7	1250	11	0	35.14
T35M	5G	304.5	860.7	137.6	1200	11	0	53.22
T36A	5M	462	929.8	148	1200	12	0	61.93
T36B	5M	264.4	1029.2	218	1150	12	0	86.41
T40A	5B	208.1	994.5	257.5	1200	12	0	114.45
T40B	5B	277.7	979.5	247.2	1200	12	0	114.47
T40C	5B	237	828.9	162.2	1200	12	0	77.27
T40D	5F	371.5	814.5	106.9	1150	12	0	52.35
T40E	5F	484.9	823.2	119.3	1150	12	0	57.12
T40F	5F	333.8	1069.8	257.9	1150	12	0	106.62
T40G	5F	299.6	1054.9	248.3	1150	12	0	103.45
T51A	5A	327.3	1050.1	455.9	1300	11	0	162.6
T51B	5A	210	983.2	397.5	1300	11	0	143.78
T51C	5B	461.4	951.9	207.8	1300	11	0	90.24
T51D	5A	141.3	1028.3	436.5	1300	11	0	157.26
T51E	5B	255.4	956.8	210.7	1300	11	0	91.06
T51F	5A	306.2	952	354.8	1350	11	0	129.28
T51G	5A	255.3	916.5	317.6	1350	11	0	117.19
T51H	5B	519.2	946.7	205.1	1300	11	0	89.01
T51J	5B	264.6	911.5	186.3	1300	11	0	82.38
T52A	5B	381.8	906.2	199.5	1200	11	0	87.76
T52B	5B	255.4	880.5	185.5	1200	11	0	82.33
T52C	5B	260.5	835.9	161.4	1200	11	0	72.25
T52D	5F	529.9	791	96.6	1200	12	0	45.94
T52E	5B	232.6	902.5	197.7	1200	11	0	86.15
T52F	5B	416.8	908.4	200.6	1200	11	0	86.81
T52G	5B	220.7	902.7	197.7	1200	12	0	87.98
T52H	5F	343.6	777.7	91.7	1200	12	0	44.1
T52J	5F	366.8	825.9	120.3	1150	12	0	56.44

T52L	5F	178.4	892.9	153.1	1150	12	0	68.78
T52M	5F	312.6	900.8	157.3	1150	12	0	69.92
T60A	5F	545.5	872.6	134	1150	12	0	64.01
T60B	5F	527	896.1	145.6	1150	12	0	68.59
T60C	5F	362.6	952.4	176.5	1150	12	0	80.13
T60D	5F	413.9	1071.5	252.1	1150	12	0	105.57
T60E	5F	197.9	884.9	144.9	1150	12	0	69.65
T60F	5F	463.2	939.8	173.7	1150	12	0	81.11
T60G	5F	359.4	1116.4	282.2	1150	12	0	119.43
T60H	5F	321.6	1277.2	389.9	1150	12	0	162.53
T60J	5F	293.4	1100.9	266.4	1150	12	0	118.11
T60K	5F	242	1075	249.6	1150	12	0	111.37
T70A	5M	314	860.8	114.3	1200	12	0	49.95
T70B	5M	276.4	973.7	182.8	1150	12	0	74.9
T70C	5M	197.6	930.9	146.5	1200	12	0	61.57
T70D	5M	332.3	1002.1	199.3	1150	12	0	80.64
T70E	5M	228.1	827.8	100.5	1200	12	0	44.81
T70F	5M	264.6	928.3	145.1	1200	12	0	61.11
T70G	5M	268.3	942	152	1200	12	0	63.28
T80A	5M	212.8	1002.3	202.8	1200	12	0	78.96
T80B	5M	233.5	927	161.7	1200	12	0	65.1
T80C	5M	314.4	793.9	99.7	1200	12	0	42.97
T80D	5M	280.2	965	181.8	1200	12	0	72.05
T90A	5M	328.5	701.4	54.9	1300	12	0	25.84
T90B	5M	402.1	966.3	177.6	1200	12	0	71.15
T90C	5M	366.5	895.8	131.3	1250	12	0	54.51
T90D	5M	374.3	808.3	87.8	1300	12	0	38.11
T90E	5M	411.8	898.6	132.7	1250	12	0	54.85
T90F	5M	281.8	975.9	170.8	1250	12	0	68.07
T90G	5M	460.2	866.3	109.6	1300	12	0	46.09
U10A	6D	418.1	1169.6	490.7	1300	13	0	185.11
U10B	6D	392.1	1068.7	409.9	1300	13	0	157.98
U10C	6D	267	1091	351	1300	13	0	137.51
U10D	6D	337	999.3	289.4	1300	13	0	116.94
U10E	6D	327.1	1034.2	312.1	1300	13	0	126.05
U10F	6D	378.9	963	225.1	1300	13	0	91.73
U10G	6D	353	981	249.3	1250	13	0	101.24
U10H	6D	457.7	923.9	228.7	1200	13	0	91.19
U10J	6K	505	877.9	133.5	1200	12	0	55.8
U10K	6K	364.3	793.3	94.3	1200	12	0	41.21
U10L	6K	307.2	758.1	67	1200	12	0	36.48
U10M	6K	280	858.2	102.6	1200	12	0	52.77
U20A	6E	293.3	1009.8	289.6	1300	14	0	129.1
U20B	6E	352.9	987.8	201.2	1300	14	0	93.86
U20C	6E	278.9	931.9	183.5	1250	14	0	85.36
U20D	6E	338.2	1040.2	232.1	1300	14	0	101.68
U20E	6K	389.8	975	190.2	1200	14	0	74.1
U20F	6K	434.7	983.4	191.3	1200	14	0	76.83
U20G	6K	493.7	894.7	142.2	1200	14	0	59.28
U20H	6E	219.6	942.9	197.7	1200	14	0	96.65
U20J	6K	678.4	840.1	94	1200	14	0	48.76
U20K	6K	270.9	949.3	165.6	1200	14	0	70.58
U20L	6K	328.5	808.5	82.9	1200	14	0	45.4
U20M	6K	359.8	925.8	131	1200	14	0	65.18
U30A	6K	375.6	967.5	175.3	1200	12	0	76.75
U30B	6K	221.2	982.4	159.5	1200	12	0	77.01
U30C	6K	241.6	999.4	192.2	1200	12	0	83.06
U30D	6K	180.6	985.7	185.3	1200	12	0	80.37
U30E	6K	290.2	1019	203.4	1200	12	0	87.33
U40A	6E	317.1	918.9	168.9	1250	14	0	80.42
U40B	6K	388.4	868	110.6	1250	14	0	48.62
U40C	6K	263.5	878.6	126	1200	14	0	55.49
U40D	6K	266.5	864.8	119.5	1200	14	0	53.19
U40E	6K	318.1	842.3	106.7	1200	14	0	51.89
U40F	6K	289.8	840.9	99.3	1250	14	0	43.67
U40G	6K	252.8	898	120.3	1250	14	0	57.04
U40H	6K	361.2	923.9	142.5	1200	14	0	66.12
U40J	6K	279.2	996.1	166.4	1250	14	0	74.44
U50A	6K	297.7	1056.3	199.6	1250	12	0	86.38
U60A	6K	104.9	981.5	161.3	1200	12	0	75.57
U60B	6K	315.5	822.3	88	1200	12	0	44.61
U60C	6K	364.5	772.6	75.5	1200	12	0	39.9
U60D	6K	184.6	887.9	119.2	1200	12	0	57.91
U60E	6K	279.9	907.1	127.6	1200	12	0	60.64
U60F	6K	272.1	966.6	156.6	1200	12	0	71.68
U70A	6K	114.5	1039.9	195.7	1200	12	0	88.88
U70B	6K	272.1	849.3	97.9	1200	12	0	48.35
U70C	6K	350.1	858.6	103	1200	12	0	52.29
U70D	6K	208.2	937.6	138.2	1200	12	0	66.75
U70E	6K	86.5	998.9	170.3	1200	12	0	79.83
U70F	6K	59.4	996.9	169.2	1200	12	0	79.03

U80B	6K	338.9	800.9	84.2	1200	12	0	44.76
U80C	6K	202.2	962.5	153	1200	12	0	71.99
U80D	6K	120.1	1047.9	200.6	1200	12	0	89.9
U80E	6K	415	830.7	95.1	1200	12	0	49.06
U80F	6K	137.4	935	139.9	1200	12	0	67.3
U80G	6K	261.2	938.5	141.7	1200	12	0	68.33
U80H	6K	243.2	1012.6	180.5	1200	12	0	82.68
U80J	6K	371.4	839.6	98.5	1200	12	0	50.38
U80K	6K	183.5	950.3	147	1200	12	0	70.24
U80L	6K	107.4	982.6	163.9	1200	12	0	76.32
V11A	6D	206.9	1223.3	611	1300	13	0	230.73
V11B	6D	252.6	1353.3	677.7	1300	13	0	254.02
V11C	6D	252.4	1038	405	1300	13	0	157.51
V11D	6J	265.9	894.3	206.8	1350	13	0	69.25
V11E	6D	192.6	1070.8	436.6	1300	13	0	169.13
V11F	6N	160.7	824.1	137.5	1400	14	0	42.9
V11G	6D	313.5	1295.1	644.2	1300	14	0	237.94
V11H	6J	132.9	986.9	277.6	1350	14	0	88.6
V11J	6J	144	830.2	172.3	1350	14	0	59.02
V11K	6N	246.8	912.2	185.4	1400	14	0	56.82
V11L	6N	311.7	738.3	97	1400	14	0	31.29
V11M	6N	154.3	741.9	95.6	1450	14	0	30.4
V12A	6H	307.1	920	184.1	1400	14	0	66.21
V12B	6H	293.3	885.3	155.8	1450	14	0	56.85
V12C	6N	154.8	799.5	93.3	1500	14	0	32.65
V12D	6H	236	1013.8	239.5	1400	14	0	83.13
V12E	6N	324.4	786	94.2	1450	14	0	33.34
V12F	6N	332.4	733.8	74.5	1450	14	0	27.13
V12G	6N	505.9	739.6	75.5	1500	14	0	26.94
V13A	6D	231.7	1279.1	529.8	1300	14	0	176.56
V13B	6J	293.8	976.1	270.3	1350	14	0	86.12
V13C	6J	255.6	822.8	177.7	1350	14	0	58.69
V13D	6J	283.4	813.8	163.6	1400	14	0	54.13
V13E	6N	280.9	707.8	87.7	1400	14	0	28.19
V14A	6N	223.9	731.8	91.3	1450	14	0	28.84
V14B	6N	170.1	713.7	66.5	1500	14	0	24.33
V14C	6N	195.2	789.9	106.2	1400	14	0	37.57
V14D	6N	631.8	714.3	70.7	1450	14	0	26.52
V14E	6N	286.6	761.3	83.1	1500	14	0	29.36
V20A	6D	267.1	1024.6	313.7	1300	13	0	125.99
V20B	6D	190.3	971.9	279.8	1300	13	0	114.9
V20C	6D	187.9	953.3	268.2	1300	13	0	111.42
V20D	6J	299.2	856.9	171.8	1350	14	0	69.07
V20E	6N	598.7	754.8	88.6	1350	14	0	35.09
V20F	6E	153.9	867.4	176.2	1300	14	0	72.46
V20G	6N	253.6	759.5	90	1350	14	0	35.3
V20H	6N	603.4	681.1	68.4	1350	14	0	27.47
V20J	6N	314	669.5	60.2	1400	14	0	24.37
V31A	6H	621.7	916.4	194.9	1400	15	0	68.84
V31B	6H	505.3	855.7	161.7	1400	15	0	58.48
V31C	6H	395.9	810	138.7	1400	15	0	51.4
V31D	6N	467.1	789.5	96	1450	15	0	34.45
V31E	6N	833.9	854.6	120	1450	15	0	42.2
V31F	6N	155.6	920.1	152.6	1450	15	0	51.67
V31G	6N	254.7	762.4	73.9	1500	15	0	27.86
V31H	6N	128.5	966.4	189.6	1400	15	0	62.46
V31J	6N	357.9	873.6	129.2	1450	15	0	45
V31K	6N	226.7	795.6	86.6	1500	15	0	31.47
V32A	6N	194.7	943	168.7	1450	15	0	56.36
V32B	6N	556.9	800.8	91.3	1500	15	0	32.86
V32C	6N	629.9	729.8	65.3	1500	15	0	24.84
V32D	6N	589.9	744	70	1500	15	0	26.3
V32E	6N	783.3	776.3	81.4	1500	15	0	29.87
V32F	6N	201.4	739	68.3	1500	15	0	25.96
V32G	6N	544.3	858.5	125	1450	15	0	43.09
V32H	6N	517.4	722.4	62.7	1500	15	0	24.09
V33A	6N	576.9	744.8	71.2	1500	15	0	27.1
V33B	6N	406.6	736.1	68.2	1500	15	0	26.07
V33C	6N	398.1	770.9	86.5	1450	15	0	31.97
V33D	6N	455.2	737.2	73.9	1450	15	0	28.08
V40A	6N	372.2	912.3	130.5	1450	15	0	48.98
V40B	6N	292.3	765.5	79.2	1400	15	0	32.75
V40C	6N	454.9	839.1	99.9	1450	15	0	39.05
V40D	6N	333.3	809.6	95.6	1400	15	0	38.01
V40E	6N	300.9	725.5	71.8	1350	15	0	30.45
V50A	6K	408.9	763.9	66.5	1300	16	0	35.14
V50B	6K	383.8	830.3	94.4	1250	16	0	46.89
V50C	6K	409.1	986.1	163.1	1250	16	0	73.43
V50D	6K	146.8	1018.9	180.4	1250	16	0	79.66
V60A	6H	106.8	891.1	162.8	1400	15	0	61.24
V60B	6H	551.7	851.1	125	1500	15	0	47.79

V60D	6H	307.9	849.6	124.5	1500	15	0	47.56
V60E	6N	747.2	717.3	56.7	1500	15	0	22.21
V60F	6N	406	770.5	87.7	1500	15	0	31.01
V60G	6N	461.4	680.3	61.1	1450	15	0	23.63
V60H	6N	354.9	702.2	64.2	1500	15	0	23.94
V60J	6N	185.9	816.9	114.5	1450	15	0	39.28
V60K	6N	228	691.2	66.6	1400	15	0	26.53
V70A	6D	280.2	1172.1	419.8	1300	13	0	163.04
V70B	6D	121.2	1088.1	359.8	1300	13	0	142.54
V70C	6J	341.5	876.8	175.9	1350	14	0	69.81
V70D	6J	198.4	810.8	142.9	1350	14	0	57.85
V70E	6N	105.3	769	98.1	1350	14	0	36.85
V70F	6N	364.5	668.8	60.5	1400	14	0	24.49
V70G	6N	504.5	664.6	59.3	1400	14	0	24.1
W11A	6M	445.1	1060.6	207.1	1300	16	0	88.56
W11B	6M	126.8	1054.1	203.3	1300	16	0	87.25
W11C	6M	382.2	1103.3	230.7	1300	16	0	97.12
W12A	6M	623.3	876.1	89.9	1450	16	0	39.54
W12B	6M	656.3	932.4	118.1	1400	16	0	50.65
W12C	6M	570.1	848.3	88.6	1400	16	0	40.05
W12D	6M	568.9	848.3	94.6	1350	16	0	43.85
W12E	6M	248.6	1041.4	164	1350	16	0	75.07
W12F	6L	399	1285.3	270.1	1300	16	0	131.37
W12G	6M	326.4	835.2	90.5	1350	16	0	42.39
W12H	6M	484.6	1038.5	163.1	1350	16	0	74.74
W12J	6L	332.1	1280.1	248	1350	16	0	125.34
W13A	6M	275.8	1135.2	252.5	1300	16	0	103.32
W13B	6M	222.4	1293.1	351.3	1300	16	0	139.8
W21A	6N	340.1	878.7	144.5	1450	15	0	51.7
W21B	6N	580.4	813.9	106.8	1500	15	0	40.27
W21C	6N	369.6	726.1	71.4	1450	15	0	27.01
W21D	6N	468.7	720.8	69.8	1450	15	0	26.56
W21E	6N	416	729.8	72.4	1450	15	0	27.85
W21F	6N	242.7	708.2	61.2	1500	15	0	23.46
W21G	6N	562.8	730	67.6	1500	15	0	26.2
W21H	6N	432.8	780	84.3	1500	15	0	31.47
W21J	6N	530	804.5	100.1	1450	15	0	36.63
W21K	6N	797.4	757.8	92.9	1450	16	0	33.86
W21L	6N	532.8	733	89.2	1400	16	0	33.03
W22A	6N	238.7	913.4	144.2	1500	15	0	54.04
W22B	6N	331.7	815.8	102.4	1500	15	0	40.4
W22C	6N	185.6	878.3	128.4	1500	15	0	49.67
W22D	6N	197.5	779	80	1500	15	0	31
W22E	6N	385.4	1055.1	218.8	1500	15	0	78.92
W22F	6N	312	803.3	88.9	1500	15	0	33.7
W22G	6N	249.4	773.9	80.5	1500	15	0	30.85
W22H	6N	306.1	740.7	69.9	1500	15	0	27.44
W22J	6N	604.9	722.4	64.4	1500	15	0	25.65
W22K	6N	475.5	753.5	73.6	1500	15	0	28.76
W22L	6N	279.3	732.5	76.8	1400	15	0	30.12
W23A	6M	413.7	833.1	88.1	1400	16	0	41.28
W23B	6M	192.8	919.6	123	1350	16	0	55.49
W23C	6L	312.6	1136.3	178.8	1350	16	0	86.96
W23D	6L	247.9	1038.6	138.8	1350	16	0	66.36
W31A	6N	369.7	804.8	97.3	1500	15	0	38.64
W31B	6N	304.3	796.2	93.9	1500	15	0	37.62
W31C	6N	171.6	895	135.1	1500	15	0	51.17
W31D	6N	294.6	787	90.6	1500	15	0	36.57
W31E	6Q	334.2	712.5	27.8	1500	15	0	9.73
W31F	6Q	583.3	692.3	25.2	1500	15	0	8.78
W31G	6Q	519.8	643.5	20	1500	15	0	7.16
W31H	6Q	322.6	650.9	28.1	1500	15	0	9.34
W31J	6Q	552.6	649.8	27.9	1500	15	0	9.45
W31K	6Q	855.3	644.8	27.3	1500	15	0	9.17
W31L	6Q	321.4	661.9	30.5	1450	15	0	10.26
W32A	6L	417.4	700.5	36	1450	16	0	22.06
W32B	6L	934.1	900.7	74.5	1450	16	0	40.2
W32C	6Q	728.2	686.3	34.9	1450	16	0	11.77
W32D	6Q	267.2	773.3	53.4	1450	16	0	17.41
W32E	6Q	455.9	769.1	52.4	1450	16	0	17.13
W32F	6Q	187.3	782.7	58.2	1400	16	0	19.15
W32G	6Q	647.5	845.9	75.6	1400	16	0	23.92
W32H	6L	1275.1	958	97.1	1400	16	0	51.05
W41A	6E	187.6	1015.7	266.9	1400	15	0	112.55
W41B	6E	305.6	937.7	221.3	1400	15	0	97.04
W41C	6E	217.3	927.2	215.2	1400	15	0	93.97
W41D	6E	238	880.5	190.3	1400	15	0	85.29
W41E	6E	303.2	837.8	169.4	1400	15	0	79.85
W41F	6E	343.4	823	154.3	1450	15	0	74.07
W41G	6E	95.8	777	134.3	1450	15	0	66.96
W42A	6E	397.4	1061	294.1	1400	15	0	118.72

W42C	6E	376.6	1017.1	266.5	1400	15	0	109.7
W42D	6E	489.4	886.6	193.4	1400	15	0	84.42
W42E	6E	231.7	833.3	166.5	1400	15	0	76.51
W42F	6E	305.5	831.9	166	1400	15	0	76.07
W42G	6E	248.2	812.2	156.6	1400	15	0	73.89
W42H	6E	272.9	775.3	133.5	1450	15	0	66.47
W42J	6E	290.5	756.5	125.7	1500	15	0	63.14
W42K	6E	416	803.1	158.9	1400	15	0	75.45
W42L	6E	250.7	764.2	134.6	1450	15	0	67.05
W42M	6E	391.6	747.4	122.2	1500	15	0	62.19
W43A	6C	248.2	779.4	152.1	1400	17	0	75.92
W43B	6C	331.7	791	157.1	1400	17	0	77.87
W43C	6C	395.1	736.1	130.3	1450	17	0	67.43
W43D	6Q	261.7	646.5	31.6	1500	18	0	10.03
W43E	6Q	264.5	587.7	24.2	1500	18	0	7.73
W43F	6Q	631.4	654.9	34.9	1500	18	0	11.03
W44A	6Q	254.7	685	38.2	1500	18	0	11.82
W44B	6Q	486.1	659.7	34	1500	18	0	10.61
W44C	6Q	314.3	631.8	29.5	1500	18	0	9.48
W44D	6Q	236.4	564.3	20.6	1500	18	0	6.56
W44E	6Q	711.4	581.1	22.6	1500	18	0	7.33
W45A	6Q	1289.1	612.9	28.6	1500	18	0	9.06
W45B	6Q	508.4	620.3	29.6	1500	18	0	9.38
W51A	6H	624	922	140	1400	15	0	51.45
W51B	6H	496.5	864.3	114.5	1400	15	0	43.45
W51C	6H	677.7	903	131.5	1400	15	0	48.06
W51D	6H	527.4	901.8	131	1400	15	0	48.2
W51E	6C	274.3	836.9	156.8	1400	15	0	77
W51F	6C	589.3	874.2	172.7	1400	15	0	82.79
W51G	6C	420.1	889.3	179.4	1400	15	0	87.3
W51H	6C	286.4	861.8	167.5	1400	15	0	82.96
W52A	6H	289.4	836.1	101.5	1400	15	0	38.44
W52B	6H	336.2	860.5	111.4	1400	15	0	41.01
W52C	6H	177.8	839.7	103.1	1400	15	0	38.19
W52D	6C	119.3	853.9	166	1400	17	0	81.03
W53A	6H	547.5	824.8	97.4	1400	15	0	37.05
W53B	6H	218.5	857.3	109.9	1400	15	0	41.59
W53C	6H	315.6	912.7	134.1	1400	15	0	49.45
W53D	6H	314.7	867.1	113.9	1400	15	0	42.18
W53E	6C	421.9	906.1	190	1400	17	0	87.4
W53F	6C	447.3	904.3	189	1400	17	0	88.59
W53G	6C	382.3	945.6	210	1400	17	0	96.76
W54A	6H	251.1	783.3	83.3	1400	17	0	33.3
W54B	6H	281.9	845.9	107.3	1400	17	0	40.28
W54C	6H	107.4	867.3	116.3	1400	17	0	43.91
W54D	6C	138.7	896.4	183.6	1400	17	0	84.29
W54E	6C	194.1	963.4	216.4	1400	17	0	99.65
W54F	6C	268.3	997.5	240.2	1400	17	0	108.73
W54G	6C	265.3	946.7	213	1400	17	0	98.71
W55A	6H	688.7	766.6	77.9	1400	17	0	31.64
W55B	6H	217.8	850.3	109	1400	17	0	40.58
W55C	6C	532.2	905	187.9	1400	17	0	88.46
W55D	6C	270.9	901.6	186.4	1400	17	0	85.91
W55E	6C	161.2	932.8	201.3	1400	17	0	99.39
W56A	6A	359.7	922	267.2	1400	17	0	181.64
W56B	6A	224.7	979.4	295	1400	17	0	199.24
W56C	6A	252.7	1164.9	395.3	1400	17	0	242.82
W56D	6A	165.7	1034.4	323.2	1400	17	0	211.82
W56E	6A	185.7	1128.7	375.6	1400	17	0	233.55
W56F	6C	199.3	906.5	169	1400	17	0	96.31
W57A	6C	593.1	824.3	178.8	1400	17	0	84.92
W57B	6Q	434	783.7	66.5	1450	18	0	20
W57C	6Q	574.5	754.8	58.6	1450	18	0	17.78
W57D	6C	366.3	862.2	196.8	1400	18	0	91.69
W57E	6Q	403	701.2	45.5	1450	18	0	13.99
W57F	6C	223.4	773.5	151	1450	18	0	74.03
W57G	6Q	623.2	644.3	34	1450	18	0	10.68
W57H	6Q	426.4	709.9	45.4	1500	18	0	13.85
W57J	6Q	521.5	627.5	30.1	1500	18	0	9.47
W57K	6Q	300.8	627.9	30.1	1500	18	0	9.42
W60A	6A	172.4	1155.7	411.2	1400	17	0	243.98
W60B	6A	142.6	1200.6	439	1400	17	0	257.27
W60C	6A	233	1161.1	414.3	1400	17	0	245.79
W60D	6C	186.9	937.4	206	1400	17	0	107.59
W60E	6Q	134	806.3	73	1450	18	0	21.91
W60F	6Q	418.1	800.6	71.5	1450	18	0	21.41
W60G	6C	221.9	911.6	187	1400	17	0	101.39
W60H	6Q	365.4	795.7	70	1450	18	0	21.14
W60J	6Q	447.4	819.1	77.1	1450	18	0	23.12
W60K	6Q	664.8	824.7	75.3	1500	18	0	22.53
W70A	6L	2587.4	768.9	42.9	1500	16	0	24.67

X11B	6P	596.6	714.2	43.9	1450	17	0	17.24
X11C	6P	318.8	715.8	44.5	1450	17	0	17.59
X11D	6B	590.4	744	87.8	1450	17	0	52.81
X11E	6B	241.4	760.5	98.3	1400	17	0	57.22
X11F	6B	182.5	820	120.4	1400	17	0	64.86
X11G	6B	263.7	866.6	180.3	1400	17	0	110.56
X11H	6B	265.1	951.2	222	1400	17	0	129.94
X11J	6B	186.2	1039.7	271.5	1400	17	0	159.89
X11K	6B	210.7	894.7	193.8	1400	17	0	118.6
X12A	6B	244.3	801.8	127.2	1400	17	0	75.37
X12B	6B	154.8	834.1	140.5	1400	17	0	80.69
X12C	6B	186.1	876.3	159.6	1400	17	0	89.84
X12D	6F	223	859.9	80.4	1400	17	0	44.72
X12E	6F	332.6	889.1	90.9	1400	17	0	47.75
X12F	6F	312.7	870.3	83.8	1400	17	0	46.26
X12G	6F	238.7	900.8	95.7	1400	17	0	50.92
X12H	6F	285.7	921.5	121	1400	17	0	58.35
X12J	6C	295.7	1158.2	231.8	1400	17	0	138.98
X12K	6F	286.2	910.6	116.1	1400	17	0	56.7
X13A	6C	244.8	1200.1	254.8	1400	17	0	147.43
X13B	6C	236.7	1156.9	231.2	1400	17	0	131.55
X13C	6C	195.2	1267	294.2	1400	17	0	156.8
X13D	6G	180.7	1185.3	268	1400	17	0	123.81
X13E	6G	211.5	1019.3	186.8	1400	17	0	92.96
X13F	6G	216.9	1006.6	181.5	1400	17	0	90.9
X13G	6Q	334.7	822.2	81.9	1400	18	0	25.58
X13H	6Q	305.5	742.4	54.1	1450	18	0	17.76
X13J	6R	789.3	676.3	32.2	1500	18	58.21	0
X13K	6R	620.6	608.5	18.9	1550	18	62.02	0
X13L	6R	286.2	605.3	18.4	1550	18	64.88	0
X14A	6C	140.8	1244	347.4	1400	17	0	210.9
X14B	6C	185.2	1228.9	338.8	1400	17	0	199.69
X14C	6C	165.8	1098	269.8	1400	17	0	159.07
X14D	6C	128.6	1138.4	289.9	1400	17	0	169.07
X14E	6G	177.3	980	132.3	1400	17	0	61.96
X14F	6C	117.5	1256.6	355	1400	17	0	213.91
X14G	6G	204.2	905.2	102.3	1450	17	0	50.05
X14H	6Q	359.8	752.4	60.2	1500	18	0	19.09
X21A	6B	264.9	763.2	145.5	1400	17	0	72.92
X21B	6B	378.3	708.3	118.5	1400	17	0	63.43
X21C	6B	311	757.4	142.6	1400	17	0	73.04
X21D	6B	219.1	733.5	130.1	1400	17	0	68.38
X21E	6B	345.1	870.9	199.8	1400	17	0	125.05
X21F	6B	396.7	757.1	105.6	1400	17	0	58.76
X21G	6B	347.3	795.5	120.5	1400	17	0	64.27
X21H	6B	228.8	1068.2	277.2	1400	17	0	161.26
X21J	6B	354.6	924.8	194.7	1400	17	0	114.25
X21K	6B	245.1	1057.7	271.1	1400	17	0	158.5
X22A	6B	251.4	998.9	283.6	1400	17	0	174.84
X22B	6B	226.6	976.6	270.9	1400	17	0	164.37
X22C	6F	366.2	936.5	103.1	1400	17	0	57.77
X22D	6C	274.4	1177.6	316.4	1400	17	0	184.8
X22E	6C	153	1136.2	291.8	1400	17	0	166.4
X22F	6F	212.4	940.4	104.5	1400	17	0	57.68
X22G	6C	107.4	1105.6	274.7	1400	17	0	162.6
X22H	6F	200.2	918.9	97.6	1400	17	0	55.04
X22J	6F	239.9	815	69.4	1400	17	0	41.64
X22K	6F	334.9	867.5	84.6	1400	17	0	47.52
X23A	6C	126.8	1101.2	252.7	1400	17	0	173.86
X23B	6C	229.1	845.4	70	1400	17	0	43.67
X23C	6C	81.3	1111.2	314	1400	17	0	183.39
X23D	6C	181.9	813.8	156.3	1400	17	0	93.5
X23E	6C	180.4	1016.1	204.1	1400	17	0	107.03
X23F	6C	309.6	820.1	64.4	1400	17	0	40.81
X23G	6F	225.1	882.4	89	1400	17	0	49.53
X23H	6F	306	882	89	1400	17	0	49.9
X24A	6Q	248.5	721.5	41.2	1450	18	0	14.09
X24B	6Q	335	710.2	38.8	1450	18	0	13.15
X24C	6Q	285.7	729.3	43.1	1450	18	0	14.48
X24D	6Q	301.8	816.1	83	1450	18	0	25.72
X24E	6R	526	646.3	27.7	1500	18	60.83	0
X24F	6R	262.1	655.2	27.8	1550	18	62.5	0
X24G	6R	619.9	595.1	18.8	1550	18	63.21	0
X24H	6R	769.3	549.9	13.3	1600	18	66.07	0
X31A	6A	230.1	1241.1	452.4	1400	17	0	341.02
X31B	6A	195.2	1241.1	452.5	1400	17	0	342.44
X31C	6A	154	1294.1	484.8	1400	17	0	356.4
X31D	6C	192	944.6	203	1400	17	0	108.16
X31E	6C	213.8	1251.9	488.2	1400	17	0	275.46
X31F	6C	94	1334.4	542.9	1400	17	0	311.47
X31G	6G	168.5	982.6	225.1	1450	17	0	113.15

X31J	6C	154.3	902.4	188.7	1400	17	0	98.15
X31K	6R	487.5	678.8	31.4	1500	18	58.57	0
X31L	6R	303.8	742.6	43.7	1550	18	57.38	0
X31M	6R	709.1	571.1	13.6	1600	18	64.52	0
X32A	6G	112.2	1037.1	261.3	1450	17	0	117.23
X32B	6G	55.3	973.2	218.6	1500	17	0	99.43
X32C	6Q	233.3	756.5	61.3	1550	18	0	19.22
X32D	6G	100	1093.4	292.9	1450	17	0	130.58
X32E	6G	78.3	896	189.3	1450	17	0	89.67
X32F	6Q	157.3	725.7	52.6	1550	18	0	16.7
X32G	6R	335.5	663	30.3	1600	18	59.88	0
X32H	6R	488.4	635.6	24.4	1650	18	60.12	0
X32J	6R	355.2	588.4	17.6	1650	18	65.6	0
X33A	6R	600.2	536.9	10.2	1650	18	68.57	0
X33B	6R	310.4	525.3	8.7	1700	18	71.31	0
X33C	6R	182.5	485.4	5.5	1750	18	76.31	0
X33D	6R	350	460	4.4	1650	18	75.83	0
X40A	6R	924.2	522.1	6.6	1900	18	67.74	0
X40B	6R	743.3	481.1	4.4	1900	18	71.07	0
X40C	6R	941.1	610.8	15.6	1750	18	62.02	0
X40D	6R	589.1	488.6	4.9	1800	18	71.07	0
Y10A	1W	1600	530	4.7	1950	18	18	63.628
Y10B	1W	1200	530	4.7	1950	18	18	50.202
Y10C	1W	6800	530	4.7	1950	18	18	55.141
Y10D	1W	7400	530	4.7	1950	18	18	483.323
Y10E	1V	2800	400	4.7	1950	18	18	488.717
Y10F	1U	1600	400	4.7	1950	18	18	51.269
Y10G	1U	4300	400	4.7	1950	18	18	52.023
Y10H	1V	800	400	4.7	1950	18	18	62.922
Y10J	1V	8500	400	4.7	1950	18	18	63.599
Y20A	1V	9000	530	14.3	1950	18	18	63.633
Y20B	1V	850	530	15	1950	18	18	48.973
Y20C	1X	6000	400	19.1	1950	18	18	42.115
Y20D	1X	850	400	19.1	1950	18	18	44.134
Y20E	1X	450	400	19.1	1950	18	18	41.449
Y20F	1X	850	400	19.1	1950	18	18	49.756
Y20G	1X	4450	400	19.1	1950	18	18	49.361
Y20H	1X	6600	300	4.2	1950	18	18	26.296
Y30A	1X	1700	300	4.2	1950	18	17	5.302
Y30B	1X	1600	500	20.9	1950	18	17	6.307
Y30C	1X	1600	450	7.7	1950	18	17	3.978
Y40A	6R	1200	500	12.1	1550	18	17	2.932
Y40B	6R	900	500	4.9	1550	18	17	2.949
Y40C	6R	960	500	4.4	1550	18	17	2.962
Y50A	6R	1200	800	75.3	1550	18	17	2.952
Y70A	6L	1800	630	29.8	1500	16	17	2.988
Z10A	3M	13636.4	220	0.1	2800	4	4	30.147
Z10B	3J	22500	330	0.3	2250	18	18	35.05
Z10C	3J	1600	330	1.2	2250	18	18	70.978
Z10D	3J	800	330	0.5	2250	18	18	16.494
Z10E	3J	15000	220	0.2	2250	18	18	30.448
Z10F	3M	9000	220	0.4	2800	4	4	30.453
Z10G	3M	9000	170	0.2	2800	4	4	32.89
Z10H	3L	8000	120	0.9	2700	4	4	69.117
Z10J	3L	600	120	0.9	2700	4	4	52.549
Z20A	3P	179263.6	250	2.6	2650	3	3	36.228
Z20B	3L	9000	113	0.8	2700	4	4	74.203
Z20C	3P	4500	60	0.1	2650	3	3	71.212
Z20D	3P	9000	80	0.2	2650	3	3	62.325
Z20E	3P	4500	60	0.1	2650	3	3	71.212
Z20F	3P	3500	42	0.1	2650	3	3	81.771

D5. EQUATIONS FOR MEMBERSHIP FUNCTIONS FOR THE ECOLOGICAL RISK ASSESSMENT

Membership functions for difference between groundwater level and root depth, and base flow versus abstraction, are cosine graphs in the form:

$$\text{Membership} = \left[\frac{1}{2} \times (\cos(((\text{I} - \text{U}) * \pi / \text{stretch}) - \pi) + 1)\right]$$

where

Membership = A value between 0 and 1

I = Input (the value given by the user/calculated by the DT for ratio of base flow to discharge or difference between water level and root depth)

U = Unfavourable limit

Stretch = Absolute value (favourable limit – unfavourable limit)

The membership function for toxins is:

$$\text{Membership} = 1 - \left[\frac{1}{2} \times (\cos((I * \pi / \text{stretch}) - \pi) + 1)\right]$$

where

I = Input (the concentration value calculated by the DT)

D6. AQUATIC ECOSYSTEM GUIDELINES *(Taken from DWAF, 1996)*

The Aquatic ecosystem guidelines for toxic constituents are list as follows:

Contaminant (ug/L)	TWQR	CEV	AEV
Acid soluble Aluminium	≤5	10	100
Un-ionised Ammonia	≤7	15	100
Total Arsenic	≤10	20	130
Atrazine	≤10	19	100
Total Cadmium	≤0.15	0.3	3
Total residual Chlorine	≤0.2	0.35	5
Dissolved Chromium(VI)	≤7	14	200
Dissolved Chromium(III)	≤12	24	340
Dissolved Copper	≤0.3	0.53	1.6
Free Cyanide	≤1	4	110
Endosulfan	≤0.01	0.02	0.2
Dissolved Fluoride	≤750	1500	2540
Dissolved Lead	≤0.2	0.5	4
Dissolved Manganese	≤180	370	1300
Total Mercury	≤0.04	0.08	1.7
Phenol	≤30	60	500
Total Selenium	≤2	5	30
Dissolved Zinc	≤2	3.6	36

Where

TWQR = Target water quality range

CEV = Chronic effect value

AEC = Acute effect value

For the rapid assessment the following ratings will be used as there are no concentrations available:

Contaminant	Rapid rating
Acid soluble Aluminium	Long-term effects
Un-ionised Ammonia	Death
Total Arsenic	Effects common
Atrazine	Death
Total Cadmium	Long-term effects
Total residual Chlorine	Effects common
Dissolved Chromium(VI)	Few effects
Dissolved Chromium(III)	Few effects
Dissolved Copper	Effects common
Free Cyanide	Few effects
Endosulfan	Death
Dissolved Fluoride	Few effects
Dissolved Lead	Death
Dissolved Manganese	No information available
Total Mercury	Long-term effects
Phenol	Death
Total Selenium	Death
Dissolved Zinc	Long-term effects

APPENDIX E

Decision Rules for Risk Assessments

E1. DECISION RULES FOR GROUNDWATER SUSTAINABLE RISK ASSESSMENT

No.	Drawdown	Blow yield	Pumping	Aquifer	Effective	Conclusion
1	F	F	F	F	F	0.00
2	F	F	F	F	U	0.00
3	F	F	F	U	F	0.00
4	F	F	F	U	U	0.00
5	F	F	U	F	F	0.00
6	F	F	U	F	U	0.00
7	F	F	U	U	F	0.00
8	F	F	U	U	U	0.00
9	F	U	F	F	F	0.00
10	F	U	F	F	U	0.00
11	F	U	F	U	F	0.00
12	F	U	F	U	U	0.00
13	F	U	U	F	F	0.00
14	F	U	U	F	U	0.00
15	F	U	U	U	F	0.00
16	F	U	U	U	U	0.00
17	U	F	F	F	F	1.00
18	U	F	F	F	U	1.00
19	U	F	F	U	F	1.00
20	U	F	F	U	U	1.00
21	U	F	U	F	F	1.00
22	U	F	U	F	U	1.00
23	U	F	U	U	F	1.00
24	U	F	U	U	U	1.00
25	U	U	F	F	F	1.00
26	U	U	F	F	U	1.00
27	U	U	F	U	F	1.00
28	U	U	F	U	U	1.00
29	U	U	U	F	F	1.00
30	U	U	U	F	U	1.00
31	U	U	U	U	F	1.00
32	U	U	U	U	U	1.00

F = favourable, U = unfavourable

E2. DECISION RULES FOR GROUNDWATER CONTAMINATION RISK ASSESSMENT

Vulnerability assessment decision rules

Rule No.	Depth to groundwater	Recharge	Aquifer media	Topography	Soil media	Vadose zone	Conclusion
1	F	F	F	F	F	F	0.00
2	F	F	F	F	F	U	0.25
3	F	F	F	F	U	F	0.10
4	F	F	F	F	U	U	0.35
5	F	F	F	U	F	F	0.05
6	F	F	F	U	F	U	0.30
7	F	F	F	U	U	F	0.15
8	F	F	F	U	U	U	0.40
9	F	F	U	F	F	F	0.15
10	F	F	U	F	F	U	0.40
11	F	F	U	F	U	F	0.25
12	F	F	U	F	U	U	0.50
13	F	F	U	U	F	F	0.20
14	F	F	U	U	F	U	0.45
15	F	F	U	U	U	F	0.30
16	F	F	U	U	U	U	0.55
17	F	U	F	F	F	F	0.20
18	F	U	F	F	F	U	0.45
19	F	U	F	F	U	F	0.30
20	F	U	F	F	U	U	0.55
21	F	U	F	U	F	F	0.25
22	F	U	F	U	F	U	0.50
23	F	U	F	U	U	F	0.35
24	F	U	F	U	U	U	0.60
25	F	U	U	F	F	F	0.35
26	F	U	U	F	F	U	0.60
27	F	U	U	F	U	F	0.45
28	F	U	U	F	U	U	0.70
29	F	U	U	U	F	F	0.40
30	F	U	U	U	F	U	0.65
31	F	U	U	U	U	F	0.50
32	F	U	U	U	U	U	0.75
33	U	F	F	F	F	F	0.25
34	U	F	F	F	F	U	0.50
35	U	F	F	F	U	F	0.35
36	U	F	F	F	U	U	0.60
37	U	F	F	U	F	F	0.30
38	U	F	F	U	F	U	0.55
39	U	F	F	U	U	F	0.40
40	U	F	F	U	U	U	0.65
41	U	F	U	F	F	F	0.40
42	U	F	U	F	F	U	0.65
43	U	F	U	F	U	F	0.50
44	U	F	U	F	U	U	0.75
45	U	F	U	U	F	F	0.45
46	U	F	U	U	F	U	0.70
47	U	F	U	U	U	F	0.55
48	U	F	U	U	U	U	0.80
49	U	U	F	F	F	F	0.45
50	U	U	F	F	F	U	0.70
51	U	U	F	F	U	F	0.55
52	U	U	F	F	U	U	0.80
53	U	U	F	U	F	F	0.50
54	U	U	F	U	F	U	0.75
55	U	U	F	U	U	F	0.60
56	U	U	F	U	U	U	0.85
57	U	U	U	F	F	F	0.60
58	U	U	U	F	F	U	0.85
59	U	U	U	F	U	F	0.70
60	U	U	U	F	U	U	0.95
61	U	U	U	U	F	F	0.65
62	U	U	U	U	F	U	0.90
63	U	U	U	U	U	F	0.75
64	U	U	U	U	U	U	1.00

F = favourable, U = unfavourable

Pollutant assessment decision rules

Rule No.	Pollutant	Duration	Properties	Conclusion
1	F	F	F	0.00
2	F	F	U	0.10
3	F	U	F	0.25
4	F	U	U	0.25
5	U	F	F	1.00
6	U	F	U	1.00
7	U	U	F	1.00
8	U	U	U	1.00

F = favourable, U = unfavourable

E3. DECISION RULES FOR GROUNDWATER HEALTH RISK ASSESSMENT

Rapid health risk assessment decision rules

	Toxicity	Carcinogeneity	Infection	Exposure	Population	Size of	Conclusion
1	F	F	F	F	F	F	0.00
2	F	F	F	F	F	U	0.15
3	F	F	F	F	U	F	0.08
4	F	F	F	F	U	U	0.23
5	F	F	F	U	F	F	0.15
6	F	F	F	U	F	U	0.31
7	F	F	F	U	U	F	0.23
8	F	F	F	U	U	U	0.38
9	F	F	U	F	F	F	1.00
10	F	F	U	F	F	U	1.00
11	F	F	U	F	U	F	1.00
12	F	F	U	F	U	U	1.00
13	F	F	U	U	F	F	1.00
14	F	F	U	U	F	U	1.00
15	F	F	U	U	U	F	1.00
16	F	F	U	U	U	U	1.00
17	F	U	F	F	F	F	1.00
18	F	U	F	F	F	U	1.00
19	F	U	F	F	U	F	1.00
20	F	U	F	F	U	U	1.00
21	F	U	F	U	F	F	1.00
22	F	U	F	U	F	U	1.00
23	F	U	F	U	U	F	1.00
24	F	U	F	U	U	U	1.00
25	F	U	U	F	F	F	1.00
26	F	U	U	F	F	U	1.00
27	F	U	U	F	U	F	1.00
28	F	U	U	F	U	U	1.00
29	F	U	U	U	F	F	1.00
30	F	U	U	U	F	U	1.00
31	F	U	U	U	U	F	1.00
32	F	U	U	U	U	U	1.00
33	U	F	F	F	F	F	1.00
34	U	F	F	F	F	U	1.00
35	U	F	F	F	U	F	1.00
36	U	F	F	F	U	U	1.00
37	U	F	F	U	F	F	1.00
38	U	F	F	U	F	U	1.00
39	U	F	F	U	U	F	1.00
40	U	F	F	U	U	U	1.00
41	U	F	U	F	F	F	1.00
42	U	F	U	F	F	U	1.00
43	U	F	U	F	U	F	1.00
44	U	F	U	F	U	U	1.00
45	U	F	U	U	F	F	1.00

46	U	F	U	U	F	U	1.00
47	U	F	U	U	U	F	1.00
48	U	F	U	U	U	U	1.00
49	U	U	F	F	F	F	1.00
50	U	U	F	F	F	U	1.00
51	U	U	F	F	U	F	1.00
52	U	U	F	F	U	U	1.00
53	U	U	F	U	F	F	1.00
54	U	U	F	U	F	U	1.00
55	U	U	F	U	U	F	1.00
56	U	U	F	U	U	U	1.00
57	U	U	U	F	F	F	1.00
58	U	U	U	F	F	U	1.00
59	U	U	U	F	U	F	1.00
60	U	U	U	F	U	U	1.00
61	U	U	U	U	F	F	1.00
62	U	U	U	U	F	U	1.00
63	U	U	U	U	U	F	1.00
64	U	U	U	U	U	U	1.00

F = favourable, U = unfavourable

Intermediate and comprehensive risk assessment decision rules

	Toxin	Infection	Radiation	Carcinogen	Size of	Conclusion
1	F	F	F	F	F	0.00
2	F	F	F	F	U	0.40
3	F	F	F	U	F	0.90
4	F	F	F	U	U	0.90
5	F	F	U	F	F	0.90
6	F	F	U	F	U	0.90
7	F	F	U	U	F	0.90
8	F	F	U	U	U	0.90
9	F	U	F	F	F	0.90
10	F	U	F	F	U	0.90
11	F	U	F	U	F	0.90
12	F	U	F	U	U	0.90
13	F	U	U	F	F	0.90
14	F	U	U	F	U	0.90
15	F	U	U	U	F	0.90
16	F	U	U	U	U	0.90
17	U	F	F	F	F	0.90
18	U	F	F	F	U	0.90
19	U	F	F	U	F	0.90
20	U	F	F	U	U	0.90
21	U	F	U	F	F	0.90
22	U	F	U	F	U	0.90
23	U	F	U	U	F	0.90
24	U	F	U	U	U	0.90
25	U	U	F	F	F	0.90
26	U	U	F	F	U	0.90
27	U	U	F	U	F	0.90
28	U	U	F	U	U	0.90
29	U	U	U	F	F	0.90
30	U	U	U	F	U	0.90
31	U	U	U	U	F	0.90
32	U	U	U	U	U	1.00

F = favourable, U = unfavourable

E4. DECISION RULES FOR GROUNDWATER ECOLOGICAL RISK ASSESSMENT

Decision rules for the quantity ecological risk assessment

Rule No.	gw-root depth	Type of dependence	Base flow	sw-gw interaction	Uniqueness of ecosytem	Conclusion
1	F	F	F	F	F	0
2	F	F	F	F	U	0.2
3	F	F	F	U	F	0.2
4	F	F	F	U	U	0.4
5	F	F	U	F	F	0.2
6	F	F	U	F	U	0.4
7	F	F	U	U	F	0.4
8	F	F	U	U	U	0.6
9	F	U	F	F	F	0.2
10	F	U	F	F	U	0.4
11	F	U	F	U	F	0.4
12	F	U	F	U	U	0.6
13	F	U	U	F	F	0.4
14	F	U	U	F	U	0.6
15	F	U	U	U	F	0.6
16	F	U	U	U	U	0.8
17	U	F	F	F	F	0.2
18	U	F	F	F	U	0.4
19	U	F	F	U	F	0.4
20	U	F	F	U	U	0.6
21	U	F	U	F	F	0.4
22	U	F	U	F	U	0.6
23	U	F	U	U	F	0.6
24	U	F	U	U	U	0.8
25	U	U	F	F	F	0.4
26	U	U	F	F	U	0.6
27	U	U	F	U	F	0.6
28	U	U	F	U	U	0.8
29	U	U	U	F	F	0.6
30	U	U	U	F	U	0.8
31	U	U	U	U	F	0.8
32	U	U	U	U	U	1

F = favourable, U = unfavourable

Decision rules for quality ecological risk assessment

Rule no.	Toxins	Duration	Conclusion
1	F	F	0.0
2	F	U	0.5
3	U	F	1
4	U	U	1

F = favourable, U = unfavourable

Summary

The limited number of water resources in South Africa has resulted in increased emphasis being placed on groundwater. Groundwater supply of acceptable quality and quantity is a very important factor in the development of communities. The availability of water for various uses is directly related to the management of water quantity, quality and/or elimination of diseases.

A risk can be defined as the probability that an adverse event will occur under specified circumstances. Effective decision-making involves the management of risks: the identification, evaluation, selection and implementation of actions to reduce risk.

The aim of the research discussed in this thesis is to develop a decision tool to aid groundwater resource managers in the task of optimising the utilisation of groundwater. The decision tool will include:

- *Information concerning aquifer parameters*: Pumping test analysis methods have been developed primarily to investigate and characterise flow within idealised confined radial flow systems. Unfortunately these assumptions are usually invalid with regard to the shallow fractured rock aquifers in South Africa. Notable attempts have been made to expand pumping test methodologies. A worthwhile method to consider when analysing a pumping test was developed by Barker (1988), where he generalised the Theis equation by including a term called the non-integer flow dimension, thereby making it applicable to arbitrary fractured confined aquifers.
- *Information concerning contaminant parameters*: Dispersivity is a scale-dependent property of an aquifer that determines the degree to which a dissolved constituent will spread in flowing groundwater. No in-depth investigation was conducted concerning this parameter, but as it plays an important role in the movement of contaminated groundwater, it is briefly discussed.
  Although matrix diffusion can influence groundwater contamination, very little research has been conducted in South Africa on this topic. The project therefore includes laboratory matrix diffusion experiments. The results of these experiments are included in the decision tool.
- *A framework for risk assessments:* the project introduces tools based on fuzzy logic to assist in decision-making by systematically considering all possibilities.

This tool takes into account the sustainability of a groundwater resource, the potential contamination of groundwater, human health risks and impacts of changes in groundwater (quantity and/or quality) on aquatic ecosystems.

- *Methods to make cost-effective decisions*: Negative impacts can place heavy burdens on society and economics. Cost-benefit-risk assessments are therefore considered to define, compare and measure benefits and costs with regards to an impact.
- *Possibilities of remediation*: Remediation forms an important component of many groundwater investigations and a few experiments were therefore conducted, the results of which were included in the decision tool. The results provide the groundwater manager with an indication of the possible success of a remediation project.

KEY WORDS: Fuzzy logic, groundwater, risk assessments, sustainability, contamination, health, aquatic ecosystems, South African Water Act, cost-benefit-risk analysis.

Opsomming

Beperkte waterbronne in Suid Afrika het tot gevolg dat groot klem op grondwater geplaas word. Genoegsame grondwater van aanvaarbare gehalte is een van die mees belangrike faktore in die ontwikkeling van gemeenskappe. Die beskikbaarheid van water vir verskeie gebruike is direk gekoppel aan die bestuur van water hoeveelhede en gehalte en/of die voorkoming van siektes.

Die doel van die navorsing wat in hierdie tesis bespreek word is die ontwikkeling van rekenaarsagteware om die waterbronbestuurder te help om die gebruik van grondwater te optimiseer. Die besluitnemingssagteware bestaan onder meer uit:

- *Inligting oor akwifeer parameters*: Die ontledingsmetodes van pomptoetse is hoofsaaklik om die karakterstieke vloei van ideaal ingeslote radiale vloei sisteme te ondersoek. Hierdie veronderstelling is ongelukkig nie geldig vir die vlak fraktuur akwifere in Suid Afrika nie. Vele pogings is al aangewend om pomptoetsmetodieke uit te brei. Een van die merkwaardigste pogings om pomptoetse te analiseer is deur Barker (1988) ontwikkel. Hy het die Theis-vergelyking veralgemeen deur 'n nie heel getal vloeidimensie by te voeg sodat dit aangewend kan word vir die gebruik in 'n arbitrêr ingeslote fraktuurakwifeer.

- *Inligting aangaande besoedelingsparameters*: Dispersiwiteit is 'n skaal afhanglike eienskap van 'n akwifeer wat die verspreidingsvermoë van opgelosde besoedeling in vloeiende grondwater bepaal. Geen in-diepte ondersoek aangaande die parameter is uitgevoer nie. Dit speel egter 'n belangrike rol in die beweging van besoedelde grondwater en as sulks word dit kortliks bespreek.

  Matriksdiffusie kan grondwaterbesoedeling beinvloed. Daar is egter tot op hede min navorsing hieroor in Suid Afrika gedoen. Hierdie navorsing sluit dus laboratorium matriksdiffusie eksperimente in. Die resultate van die eksperimente is in die besluitnemingssagteware opgeneem.

- *Raamwerk vir risikobepalings*: Die projek stel 'fuzzy logic' gebasseerde metodiek bekend wat die besluitnemingsproses aanhelp met die sistematiese oorweging van alle moontlikhede. Hierdie metodiek neem in aanmerking die volhoubaarheid van 'n grondwaterbron, die besoedeling van grondwater, gesondheidsrisiko en

die invloed van die verandering van grondwater (hoeveelhede en gehalte) op akwatiese ekosisteme.

- *Metodes vir koste-voordeel besluitneming:* Negatiewe invloede kan 'n groot impak op die samelewing en ekonomie tot gevolg hê. Koste-voordeel-risiko studies word gebruik om so 'n invloed te definieer, te vergelyk en die kostes en voordele te bepaal.
- *Moontlikhede van remediasie*: Remediasie is 'n belangrike komponent van grondwaterondersoeke. Eksperimente is hieroor gedoen en die resultate is in die besluitnemingssagteware ingesluit. Hierdie resultate sal die bestuurders van grondwaterbronne 'n aanduiding gee van moontlike sukses wat behaal kan word deur middel van 'n remediasie proses.