GUIDELINES FOR ASSESSING SINGLE BOREHOLE YIELDS IN SECONDARY AQUIFERS

THESIS

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ABSTRACT

The motivation for this research project arose from the realisation that many South African rural water supply schemes fail due to the over abstraction of groundwater from single boreholes. The main reason for this mis-management of groundwater is a result of inappropriate borehole yield recommendation methods. This research project set out to review existing borehole yield assessment methods and establish new methods which take the shortcomings of existing methods into account. The study is concerned with borehole yield assessment methods applicable to secondary aquifers, since these aquifers are by far the most common in South Africa.

The yield assessment methods have been grouped into those that are based on aquifer yield analyses, and on the analysis of single borehole test pump data. In order to assess which methods give suitable yield recommendations, it was necessary to compare the yields obtained using the various methods, with established yields from production boreholes.

The focus of the aquifer yield component of the study, was to develop a method for estimating the proportion of recharge that can be abstracted from a single borehole located in a relatively small aquifer. The method was developed by computer simulations of aquifers with different hydraulic properties, and by establishing a formula which describes the relationship between recharge and the abstractable proportion of recharge. Under specific hydrogeological conditions, the recharge based method proved to be reliable in relation to established yields from production boreholes.

Of the borehole yield assessment methods based on the analysis of test pump data, none of the existing methods proved to be reliable. However, the yields obtained using the two newly developed methods compared favourably to the established yield of existing production boreholes. Both of these methods are based on the application of the Cooper-Jacob approximation of the Theis equation.

This study reviews existing methods and presents newly developed methods for recommending borehole abstraction rates in secondary aquifers. While existing borehole yield assessment methods were found to be unreliable, some of the newly developed methods, if correctly applied, give acceptable yield recommendations.

1. INTRODUCTION

1.1 THESIS BACKGROUND

A large percentage of the approximately 14 000 rural villages in South Africa do not have any formal water supply schemes and will need to obtain their domestic water from boreholes. Most of these communities will need to rely on diesel or electricity-driven pumps for their domestic supply to meet the Department of Water Affairs and Forestry's (DWAF) "basic" level of service, which is defined as 25 litres per capita per day within 200 m of each dwelling (DWAF, 1994). In most cases underprivileged rural communities can at best only afford to operate and maintain one pumping system, which makes it increasingly important for the recommended borehole yield to be reliable and not too conservative.

This research aims to review and establish methods for recommending single borehole abstraction rates in secondary aquifers, which constitute more than 90% of the aquifers in South Africa (Kirchner and Van Tonder, 1995). Currently drillers, pump test contractors, engineers and hydrogeologists all recommend groundwater abstraction rates and the methods used vary considerably. While some groundwater abstraction rates are based on borehole yield analyses alone, others are based on both an aquifer and a borehole yield analysis. This study looks at methods of recommending borehole abstraction rates based on the analysis of test pump data and on an assessment of aquifer yields. Reference is frequently made to boreholes which are located in small headwater catchments because many rural villages are located on hilltops or on slopes in highly undulating topography. Commonly used terms are defined at the end of this chapter.

The recommended borehole yield in this study is defined as the maximum daily rate at which a borehole can be pumped on a sustainable basis. This yield may be controlled by the aquifer's transmissivity which governs the rate at which water can enter the borehole during pumping, the aquifer's storage, or the aquifer's recharge. On the one hand, an aquifer may receive a substantial amount of water through recharge and hold a vast amount of water in storage, but it can only yield a small percentage of the available groundwater due to its limited transmissivity. On the other hand, an aquifer may have highly localised transmissive zones, but limited recharge or storage and therefore may not be able to consistently supply water to a high yielding borehole. For these reasons, this study is concerned with both borehole and aquifer yield assessment methods.

The borehole yield assessment methods, some of which have been developed during this study, are based on constant discharge and recovery tests which are performed on the borehole. Additional parameters have been added to existing aquifer yield assessment methods, in order to obtain a rough estimate of the yield that an aquifer could supply to a single borehole. The aquifer yield assessment methods are based on recharge to the aquifer, the volume of water held by the aquifer in storage and the rate at which water can pass through the aquifer, or its throughflow.

Although the concept of obtaining even an estimate of a borehole's yield from an aquifer yield assessment may appear futile, it is specifically because of the nature of many South African aquifers that this idea was pursued. Due to South Africa's predominantly semi-arid climate and hard rock aquifers which are commonly characterised by low porosities and permeabilities, the volume of groundwater stored in the aquifers and the rate at which water can enter the aquifers, can limit their exploitation potential. This is of particular concern in small aquifers with narrow transmissive zones, like those associated with dykes and faults, where initial borehole yields may be relatively high, but the aquifer's storage or recharge is limited.

The focus of the aquifer yield assessment methods was not to develop methods of determining an aquifer's recharge, storage or throughflow, as these have previously been developed, but rather to establish a way of estimating the proportion of an aquifer's exploitation potential which could be abstracted by a single borehole. In a regional groundwater exploitation potential study in the Eastern Cape Province, DWAF (1995) took the abstractable proportion of groundwater to be 50%. While this may be an acceptable starting point on a regional basis to determine the groundwater exploitation potential, clearly it cannot be used for site specific cases where local conditions would influence the proportion of groundwater that a single borehole may abstract. The greater portion of this aquifer yield assessment study is concerned with establishing a method for determining a site specific estimate of the proportion of groundwater that a single borehole can abstract.

1.2 AIMS AND OBJECTIVES

The project aims to review existing methods for recommending single borehole abstraction rates in secondary aquifers as well as to develop new methods. The specific objectives are as follows:

i) to assess existing methods for recommending borehole yields in secondary aquifers;
ii) to develop new methods for recommending borehole yields in secondary aquifers;
iii) to assess existing methods of quantifying aquifer yields;
iv) to develop new methods of establishing the proportion of aquifer yields which a single borehole can abstract;
v) to establish which methods are best suited to secondary aquifers.

1.3 RESEARCH REQUIREMENTS AND THESIS LAYOUT

1.3.1 Research requirements

To achieve the stated objectives, the following requirements have been identified:

- In relation to objective i), a description of existing methods for recommending borehole abstraction rates based on test pump data analysis;
- In relation to objective ii), the adaptation of existing methods and/or the development of new methods for recommending borehole abstraction rates based on test pump data analysis;
- In relation to objective iii), a description of existing methods for quantifying an aquifer's exploitation potential;
- In relation to objectives iii) and iv), the identification of sources for obtaining recharge values and the comparison of regional recharge estimation methods;
- In relation to objective iv), the establishing of a method to estimate the proportion of recharge to an aquifer that a single borehole can abstract;
- In relation to objectives i), iii) and v), the comparison of methods for recommending borehole abstraction rates with data from monitored boreholes, and the establishing of which methods are

most suited to secondary aquifers.

At the outset of this study it was apparent that objective v) and the last identified research requirement could be difficult to meet because of problems associated with verifying the yield assessment methods. These problems included the following: Firstly, it would be difficult to accurately establish a borehole's maximum sustainable daily yield, even if abstraction, water level and rainfall data existed. Secondly, obtaining such data from which to estimate the borehole's maximum sustainable daily yield would be an ongoing difficulty. And thirdly, the information required to apply the aquifer yield assessment methods would be difficult to obtain. For example, in applying the newly developed yield assessment method which is based on recharge, it is necessary to estimate the geographical surface area which contributes to aquifer recharge. This information is seldom contained in groundwater reports.

Although verification of the yield assessment methods, and in particular, the methods based on aquifer yields was always going to be a problem, undertaking the study was still possible. In order to assess single borehole yields, existing yield assessment methods need reviewing, and, within the context of South Africa's predominantly fractured rock aquifers, new methods which consider aquifer yields and which are based on the analysis of test pump data, need to be developed.

1.3.2 Thesis layout

Objectives iii) and iv) are addressed in Chapters 2, 3 and 4 which deal with aquifer yield assessments. Chapter 2 describes how an aquifer's exploitation potential is determined using recharge. The chapter presents a brief overview of recharge processes, compares regional recharge estimation methods, and concludes by recommending regional recharge estimation methods which could be used if no local values are available.

The aim of this study is to assess and develop methods for estimating single borehole yields. For this reason, the greater portion of the aquifer yield assessment study is concerned with establishing a method for determining a site specific estimate of the proportion of groundwater abstractable from a single borehole. The method, which was developed by simulating hypothetical aquifers with a finite difference groundwater model, is presented in Chapter 3.

Chapters 4 and 5 present methods of determining an aquifer's exploitation potential based on aquifer storage and throughflow.

Objectives i) and ii) are addresses in Chapter 6 which focuses on borehole yield assessments based on test pump data. The interpretation of test pump data is discussed before presenting existing and new methods for estimating borehole yields.

Objective v) is addressed in Chapters 7 and 8. Chapter 7 compares the yield assessment methods previously described to established borehole yields. Chapter 8 summarises the results obtained in the previous chapter, discusses each yield assessment method and describes the conditions under which they could be applied.

1.4 DEFINITION OF TERMS

The following are some commonly used terms:

Secondary aquifers
Secondary openings originate in hard-rock formations through tectonic deformation, weathering and unloading by erosion. They may be planar when related to joint, bedding and fault planes or three dimensional when related to pores in disintegrated and decomposed rock. Geological formations capable of yielding water to boreholes through secondary openings are termed secondary aquifers. (Vegter 1990).

Fractured rock aquifers
Secondary aquifers which derive their permeability primarily from fracturing are termed fractured rock aquifers.

Groundwater recharge
Groundwater recharge ultimately defines the volume of water that can be abstracted from an aquifer over a long term. It is defined by Lerner et al. (1990) as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. The main controlling factors of groundwater recharge are: precipitation, infiltration from rivers and dams, geology and soil, vegetation and land-use, topography and landform.

Storage and storativity
Two important properties related to the volume of water stored in an aquifer are porosity and storativity. The porosity of a formation is the fraction of the aquifer's volume which consists of openings, and is therefore an index of the aquifer's ability to store water. Of more importance, is the fraction of water in storage which can be released in response to pumping. A storage coefficient or storativity is defined as the volume of water that an aquifer releases from or takes into storage, per unit surface area of the aquifer, per unit change in the component of head normal to that surface (Todd, 1980). It is a dimensionless quantity involving a volume of water per volume of aquifer.

Transmissivity
The property of a water-bearing formation that relates to its ability to transmit water is called hydraulic conductivity. Hydraulic conductivity indicates the quantity of water that will flow through a unit cross-sectional area under a hydraulic gradient of one at a specified temperature (Driscoll, 1986). It is often more convenient to express the ability of an aquifer to conduct water across its entire thickness. In this case hydraulic conductivity is expressed as a transmissivity, which is the product of hydraulic conductivity times aquifer depth. Transmissivity (T) may be defined as the rate at which water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient (Todd, 1980). It follows that:

$$T = K \cdot b = (m/day)(m) = m^2/day \qquad \text{eq.1.1}$$

where:

K = hydraulic conductivity
b = saturated thickness of the aquifer

Aquifer exploitation potential

The exploitation potential of an aquifer can be seen as the volume of water that can be abstracted on a long term basis without exhausting the resource (DWAF, 1993). This long-term yield is dependant on recharge due to rainfall, underground in- and outflow and groundwater storage. (Kirchner et al., 1995).

2. GROUNDWATER RESOURCE EVALUATION BASED ON RECHARGE

2.1 INTRODUCTION

Recharge ultimately defines the long term, abstractable volume of water from an aquifer. An estimate of recharge is particularly important in small, highly transmissive aquifers where short-term abstraction rates can be far greater than recharge rates. Common examples of such aquifers are the linear secondary aquifers associated with faults and dolerite dykes. These aquifers may be vulnerable to over-pumping, especially in semi-arid parts of the country where the exploitable proportion of recharge may be very low. The problem of recommending abstraction rates which exceed recharge rates could possibly be averted if the recharge, and the abstractable percentage of recharge could be estimated.

The annual exploitation potential of an aquifer based on recharge to the aquifer (E_r) in m^3/a is calculated using the following formula:

$$E_r = A \,.\, R \,.\, D \qquad \text{eq.2.1}$$

where:

A = the area over which recharge to the aquifer can take place (m^2)
R = recharge to the aquifer (m/a)
D = abstractable proportion of recharge

Extensive research on recharge estimation methods has been done. Connelly et al. (1989) developed a sizable bibliography which pays particular attention to soil properties and their relation to groundwater recharge. The most recent local study resulted in a comprehensive manual which includes those methods appropriate to South Africa's predominantly semi-arid environment (Bredenkamp et al., 1995). This chapter summarises recharge values obtained from studies conducted in Southern Africa, and presents regional recharge formulae which could be used to obtain an estimate of recharge (R in equation 2.1) if no local values are available. The focus of the recharge component of this project is covered in the following chapter, which presents a method to establish the abstractable percentage of recharge (D in equation 2.1). Chapter 3 also discusses geological factors to consider when estimating the area over which recharge to the aquifer can take place (A in equation 2.1).

It must be emphasised that groundwater recharge is one of the most difficult of all hydrological components to determine, especially in fractured rocks and in arid regions where recharge can be extremely variable in space and time (Allison, 1988). The process of recharge from rainfall is determined by inter-related, complex factors which include virtually the entire hydrological cycle (Connelly et al., 1989). Because of the critical role recharge plays in determining the available groundwater resource, and even though estimations are prone to large errors, it is common practice for a first approximation to be made using limited available data and extrapolation from elsewhere (Parsons, 1994). Gee and Hillel (1988) argue that recharge estimates in arid environments, which are based on a fraction of annual precipitation, ignore the complex nature of recharge processes and are therefore deceptive and highly misleading. However, Gieske (1992) recognises the problems in obtaining site specific recharge values;

and, with respect to long-term replenishment and annual variability, he considers the expression of recharge as a function of rainfall as the only practical way to obtain an initial recharge value. While acknowledging and describing the complexity of recharge processes, Bredenkamp et al. (1995) present several locally developed rainfall-recharge relationship formulae which correspond reasonably to observed data. They also stress that such estimates, even if they only yield provisional annual estimates, do allow for an assessment of the potential for groundwater exploitation, and thus the viability of new development projects. For this reason, and because recharge-limited aquifers are vulnerable to over-utilization, the recharge based method of estimating groundwater abstraction potential has been included in this study.

2.2 GROUNDWATER RECHARGE - A BRIEF OVERVIEW

2.2.1 Recharge processes

In order to appreciate the complexity of recharge processes, and thus respect the limitations of the simple rainfall-recharge relationships presented, a brief description of recharge processes is given (adapted from Sami, 1994). For the purposes of this study, however, it has not been necessary to describe and critique each recharge estimation method.

In simple terms, groundwater recharge can be described as the downward flow of water which reaches the water table and forms an addition to the groundwater reservoir (Lerner et. al., 1990). Water entering an aquifer may follow preferential pathways via fractures, drain through a column of soil, or infiltrate from river channels, ponds or dams.

When rain falls to earth some fraction of it is intercepted by trees, plants and buildings. Most of this does not reach the ground and is subsequently lost by evaporation. This component is known as interception loss. During frequent and brief low intensity events, interception loss may absorb a large fraction of the total rainfall. As a result, such events are the least effective from a water resource point of view.

During larger rainfall events, water that reaches the ground surface may follow several pathways. A component of it evaporates immediately from the soil surface while another infiltrates into the soil. Rainfall may enter the ground at a maximum rate defined as the infiltration capacity. This rate is controlled by soil texture and structure, as well as surface conditions and storm duration. Water entering the soil replenishes soil moisture storage if it is below field capacity. This capacity is defined as the maximum volume of water retainable by a soil against gravity. This water will subsequently be used by plants or evaporated directly. As field capacity is approached, soil water flow becomes increasingly important. Water may then flow laterally above a less permeable layer until it reaches a stream channel, or it may continue downward contributing to recharge. Since infiltration capacities and field capacities define thresholds which control the movement of water through the soil, they are important attributes to consider in groundwater recharge studies.

In regions where soils are relatively thick and rainfall is low, soil moisture may rarely exceed field capacity, therefore, recharge through the soil seldom takes place. Recharge in such regions is dependent on isolated areas where soils may be shallow and field capacities are exceeded locally, or on areas where there are fractured rock outcrops at the surface. The existence of large macropores (large pore spaces such as animal burrows, root channels, worm and termite casts) may also provide an important pathway for rainfall to bypass the soil mass and contribute to recharge. Numerous studies have shown that in semi-arid areas, which includes most of South Africa, very little flow percolates through the soil matrix to any significant depth, even with high rainfall (e.g. Lloyd, 1986; Sami, 1992; Kirchner et al., 1991). In such areas aquifers are recharged predominantly by indirect flowpaths and preferential pathways (Kirchner et al 1991; Rushton, 1987; Sharma and Hughes, 1985).

If the intensity of rainfall exceeds the evaporation and infiltration rates, water will begin to collect on the surface in what is referred to as depression storage. Once these depressions fill and begin to run over, overland flow will then form in rills, small channels or as sheet flow. A fraction of overland flow may re-infiltrate into the soil if it runs over an area with a higher infiltration capacity. The portion of overland flow that enters stream channels is termed surface runoff. Even though surface runoff carries water away from a region it may still contribute to recharge. If runoff flows over permeable material in a stream channel, a component of it, termed transmission losses, may seep into the channel bed and contribute to recharge. The proportion of water that ultimately enters the aquifer will depend on the ability of the aquifer to accept it. This is a function of the aquifer's permeability and storage capacity.

2.2.2 Methods for estimating recharge

Numerous methods are used to estimate recharge rates and all have their limitations. Both Simmers (1987) and Bredenkamp, et al. (1995) note that at present no single estimation technique has been identified which does not give suspect results. For this reason, some form of averaging needs to be applied to several techniques when accurate values are required (Bredenkamp et al., 1995). In general, recharge estimation techniques can be divided into physical and chemical methods. Physical methods attempt to estimate recharge from water balances calculated either from hydrometeorologic measurements, direct estimates of soil water fluxes based on soil physics or changes in the aquifer's saturated volume based on water table fluctuations. Chemical methods are based on the distribution of a tracer (commonly ^{2}H, ^{3}H, ^{14}C, ^{18}O and Cl) in the saturated or unsaturated zone.

Water balances are of limited use in semi-arid regions since the recharge component is small in relation to errors in the measurement of evapotranspiration, runoff and precipitation. Gee and Hillel (1988) have shown that the accumulation of the error term in the recharge estimate of a water balance has been found to exceed several hundred percent. Methods which rely on the direct measurement of soil water fluxes are problematic because fluxes are low and difficult to detect (Lerner et al. 1990). Kirchner et al. (1991) attempted to estimate recharge at Dewetsdorp and De Aar directly, and found that none of the techniques provided meaningful results. The drawback of these methods is that they assume that flow takes place through a soil matrix, rather than preferred pathways such as macro-pores and joints in rock outcrops. In arid areas, such localised recharge is likely to predominate. This is because large storm thresholds are required to overcome the substantial soil moisture deficits and initiate direct recharge through the soil matrix (Lloyd, 1986). A problem with water table fluctuation measurements is that they require accurate estimates of aquifer parameters in order to equate changes in saturated volume to recharge (Rushton, 1987). In fractured rock aquifers, these parameters are rarely uniform.

While there are numerous problems with physical recharge measurement techniques, equal concern needs to be expressed as to whether the values obtained from point measurements are representative for the specified area of interest. Allison (1988) expresses this concern when he concluded that the most important problem to overcome in the estimation of groundwater recharge is probably the assessment and prediction of its spacial variability.

Certain chemical recharge estimation techniques tend to overcome some of the spacial variability problems. For example, a tracer's concentration, like the chloride concentration in rainfall, should represent a spatially uniform concentration in the soil surface (Lerner et al., 1990). Their reliability in certain environments, however, may also be questionable. For example, the accumulation of chloride in the soil by evapotranspiration in dry areas, or its elevated concentrations in coastal areas could undermine the assumptions on which the method is based (Allison, 1988). The chloride concentrations in rain water may be very low and therefore difficult to accurately quantify. Where aquifers store sufficient water, the chemical methods have the advantage in that data collected may represent many years of recharge from which a historical record can be derived (Allison et al., 1985). In contrast, direct physical methods only provide data over the duration of the monitoring period.

Recharge estimation methods, including both physical and chemical, can be grouped in the following manner (abbreviations and examples have been placed in brackets):

The unsaturated zone
- lysimeter studies;
- soil moisture flow and balances;
- chloride profiles;
- radioisotopes (e.g. Tritium & ^{14}C);
- stable isotopes (e.g. ^{18}O & ^{2}H).

The saturated zone
- analysis of borehole water level fluctuations (groundwater hydrographs; the cumulative rainfall departure method - CRD);
- aquifer water balances;
- analysis of spring flow;
- saturated volume fluctuations (SVF);

Numerical modelling (of groundwater flow and the water balance)
- inverse groundwater modelling to calibrate recharge so that simulated heads match observed heads;
- hydrological models which consider groundwater recharge to be via porous media, rather than preferential pathways (e.g. ACRU);
- mathematical regression models (e.g. Direct Parameter Estimation method - DPE).

Steady state flow approximations (based on Darcy's Law)

Rainfall-recharge relationships.

2.3 RECHARGE VALUES OBTAINED FROM STUDIES IN SOUTHERN AFRICA

Table 2.1 summarises the findings of recharge studies that have taken place on a variety of secondary aquifers. Although a representative sample was not available for granitic aquifers, this summary includes results from two granitic aquifers located in northern South Africa. The same aquifer categories that were used in the recharge manual written by Bredenkamp et al. (1995) have been used in this report. While the high recharge values found in dolomitic aquifers can be attributed to their high degree of secondary porosity; in mountainous sedimentary aquifers, the high rainfall, shallow soils and outcropping fractured rocks (which facilitate flow in preferential pathways), contribute to their high recharge values. The low rainfall, lack of widespread secondary porosity and, in places deep soils, contribute to the low recharge values found in the Karoo, granitic and Kalahari aquifers.

Table 2.1 Groundwater recharge estimates

AQUIFER	LOCATION	MAP (mm/a)	RECHARGE (mm/a)	RECHARGE (% MAP)	METHOD	REFERENCE
Karoo:						
Fractured	Dewetsdorp	587	9.5 - 21.3	1.6 - 3.6	SVF	Kirchner et al., 1991
sedimentary	De Aar	287	4.0 - 12.6	1.4 - 4.4	SVF	Kirchner et al., 1991
rocks	Williston	176	2.5 - 3.2	1.4 - 1.8	Water balance	Woodford, pers comm.
	Bedford	483	1.4 - 12	0.3 - 2.5	VTI	Sami & Hughes, 1996
	Kat River	641	2.0 - 26	0.3 - 4.1	VTI	Sami, 1994
	Thornhill	470	4.5 - 8.6	1.0 - 1.8	MODFLOW	Sami & Murray, 1995
	Beaufort West	235	4.7	2.0	Water balance	Parsons, 1994
Basalt	Sprinbok flats	571	5.5 - 99	1.0 - 17.3	CMB	Bredenkamp et al., 1995
Granite	Dendron	440	3 - 35.2	0.7 - 8.0	CMB	Bredenkamp et al., 1995
	Coetzersdam	450	10 - 14	2.2 - 3.1	SVF	Bredenkamp et al., 1995
Sedimentary hard rock aquifers in mountain catchments	Pretoria/ Rietondale	670	54 - 160	8.1 - 23.9	Various	Bredenkamp et al., 1995
	De Hoek	1852	19.9 - 290	1.1 - 15.7	Various	Connelly et al., 1989
	Rustenburg	749	114	15.2	Hydrograph	Bredenkamp et al., 1995
	Zachariashoek	1061	319	30.1	Hydrograph	Bredenkamp et al., 1995
Dolomites	Grootfontein	560	26.7 - 48	4.8 - 8.6	Various	Bredenkamp et al., 1995
	Rietpoort	532	49.3 - 60	9.3 - 11.3	Various	Bredenkamp et al., 1995
	Western Areas	700	54 - 175	7.7 - 25	Various	Bredenkamp et al., 1995
	Kuruman	460	36 - 44	7.8 - 9.6	Various	Bredenkamp et al., 1995
	Sishen	386	49	12.7	SVF	Bredenkamp et al., 1995
	Pering	460	84 - 146	18.3 - 31.7	Various	Bredenkamp et al., 1995
	Potgietetersrus	573	9.2 - 34	1.6 - 5.9	Various	Bredenkamp et al., 1995
Kalahari / Karoo	Bray	400	3.7	0.9	CMB	Bredenkamp et al., 1995
	Dimaje	400	2.6 - 2.9	0.7	CMB	GCS, 1991
	Jwaneng	400	0.2 - 6.2	0.1 - 1.6	Isotope	Bredenkamp et al., 1995
	Lethlhakeng	420	1.1 - 5.7	0.3 - 1.4	Various	Bredenkamp et al., 1995

KEY:

SVF	Saturated Volume Fluctuation	Various	These include more than one of the following: CMB, spring flow, Tritium profile, SVF, Hill method, CRD method, DPE method, Darcy flow/Dynamic model, Hydrological model. Very low values obtained from Carbon and Tritium age methods were excluded.
ACRUWAT	A moisture budget model		
CMB	Chloride Mass Balance		
VTI	A variable time interval rainfall/runoff model with groundwater components		
MODFLOW	Inverse modelling using a finite difference model		
Tritium	Tritium profile		
GCS	Geotechnical Consulting Services	Woodford, A.	Geohydrologist, DWAF

2.4 REGIONAL RECHARGE ESTIMATES

2.4.1 Rainfall-recharge relationships

In order to extrapolate point recharge estimates to other areas, regional recharge estimation methods have been developed. The simplest empirical formula takes recharge (R) as a proportion (a) of precipitation (P):

$$R = a \cdot P \qquad \text{eq.2.2}$$

Equation 2.2 assumes that recharge is a constant fraction of rainfall. In some environments, particularly in arid and semi-arid areas, no recharge may be experienced after short, low intensity rainfall events (Parsons, 1994). Rather than considering recharge from rainfall events, it is commonly averaged over a year, and mean annual precipitation (MAP) is used as the P-value. For example, 5 % MAP was commonly used to represent recharge to Karoo aquifers (Seward, 1988; Parsons, 1987; Vandoolhaeghe, 1985; Woodford, 1984).

The next level of formula includes a threshold (P_{min} or P_{av}) below which recharge is unlikely. Such formulae are of the form:

$$R = a\,(P - P_{min}) \qquad P \geq P_{min} \qquad \text{eq.2.3}$$

or

$$R = (P - P_{av}) \qquad \text{eq.2.4}$$

where:

P_{min} = minimum precipitation
P_{av} = average precipitation

Kirchner et al. (1991) obtained a figure of 4.6% of MAP in excess of 263 mm, in a study of De Aar and Dewetsdorp which focussed on saturated volume fluctuations. Taking soil thickness into account, Kirchner et al. (1991) produced the following formulae:

Thin soil cover:	$R = 0.06\,(MAP - 120)$ [mm]	eq.2.5
Thick soil cover:	$R = 0.023\,(MAP - 51)$ [mm]	eq.2.6
Alluvial cover:	$R = 0.12\,(MAP - 20)$ [mm]	eq.2.7

In a study of spring flow from Karoo aquifers, Kok (1992) derived a value of 8% of MAP in excess of a threshold of 100 mm. In comparison to equations 2.5 to 2.7 and to the values presented in Table 2.1, Kok's figure of 8 % MAP appears to be high. Possibly Kok underestimated the area contributing to recharge, or the springs studied were in high recharge areas. The latter reason seems to be more plausible, since springs are commonly located on hill slopes where thin soils and orographic rainfall contribute to higher than average recharge. This appears to be the case for the Bedford spring which was part of Kok's study. While Kok's recharge value from a headwater spring was 36 mm/a, Sami and Hughes (1996) estimated regional recharge to be 4.5 mm/a in the nearby low lying areas. Kok limited the error in estimating the contributing area by only considering cold springs (< 25° C). Here, the catchment area above the spring was taken as the contributing area; whereas, in thermal springs water may have arisen from well below the surface, making it virtually impossible to determine their contributing areas. This example highlights how localised recharge can be, and shows how rainfall-recharge relationships which have been developed from point studies may not be transferable to regional areas.

Many rainfall-recharge relationships have been developed for dolomitic aquifers, and not all are linear. Bredenkamp (1978 and 1990) plotted recharge estimates from dolomitic aquifers in different areas, and showed that a linear relationship is obtained above an annual rainfall of 313 mm. This was adjusted to give the following general formula (Bredenkamp et al., 1995):

$$R = 0.32\ (MAP - 360)\ [mm] \qquad \text{eq.2.8}$$

In the case of mountainous catchments, Bredenkamp et al. (1995) adopted the view that the base flow component of stream flow can be used to estimate groundwater recharge. This relies on assumptions which may not necessarily hold true since it assumes that base flow can reliably be separated from total flow, and that all the recharge is derived from the delineated catchment. When relating base flow to MAP in mountainous catchments, representative rainfall data can be problematic. Because of steep slopes, orographic rainfall variations can be significant, and rain gauges are unlikely to reflect the true average precipitation over the catchments. Base flow studies in several mountainous catchments have been collated to produce the general formula (Bredenkamp et al. 1995):

$$R = 0.73\ (P_{av} - 480)\ [mm] \qquad \text{eq.2.9}$$

Numerous other rainfall-recharge relationships have been developed from point studies of South African aquifers. Some of the more complex formulae do not necessarily preserve linearity, for example:

$$R = a\ (P / P_{av})\ P \qquad \text{eq.2.10}$$

and

$$R = a\ .\ P_{av}\ (1 - b \times P_{av} / P) \qquad \text{eq.2.11}$$

where:

a and b are empirical parameters

While equation 2.10 shows that recharge varies proportionally to the deviation of rainfall from the average value, equation 2.11 assumes that the ineffective portion of rainfall varies, depending on the extent of the rainfall deviation from the long-term average. DWAF has used the following relationship to obtain a first estimate of groundwater recharge (M. Smart and A. Woodford, pers comm.):

$$R = (MAP)^2/10000\ [mm] \qquad \text{eq.2.12}$$

This formula translates to using 1% of MAP where MAP = 100 mm; 2% of MAP where MAP = 200 mm; etc.

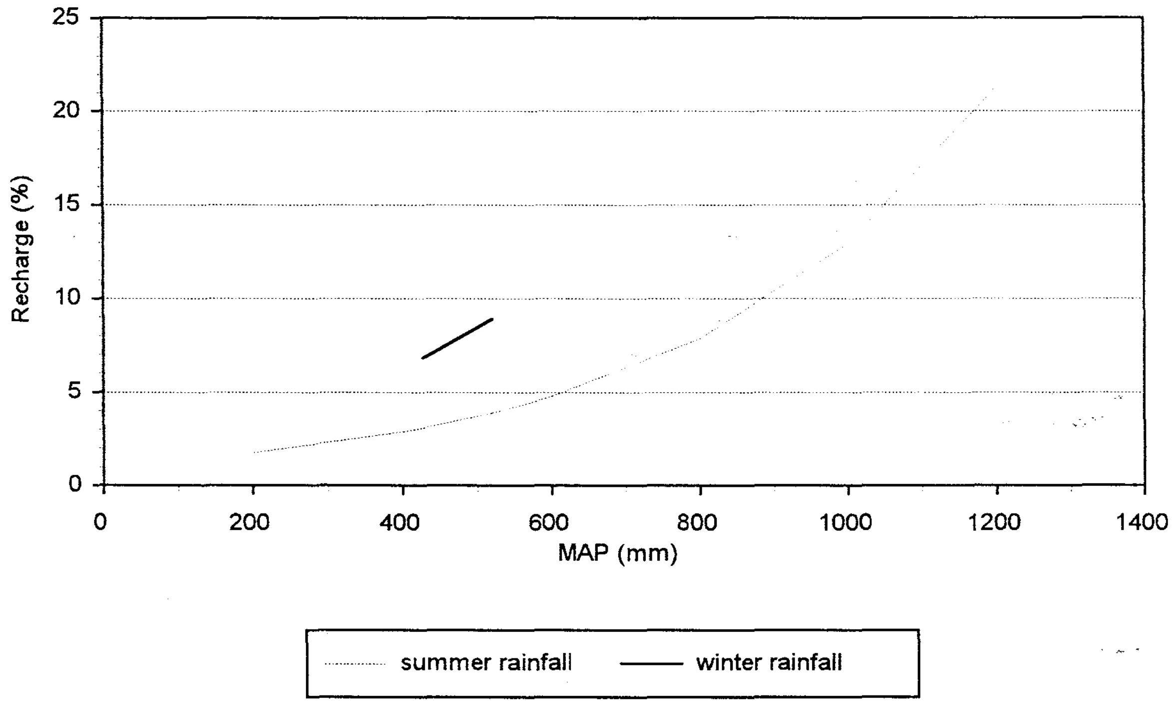
The three main criticisms of simple rainfall-recharge formulae are:

- relationships may not be transferable to areas other than those in which they were derived;

- they ignore temporal distribution of rainfall;
- their accuracy is dependant on the accuracy of the recharge estimates from which the relationship was derived.

In 1970, Enslin (Bredenkamp et al., 1995: p.258) produced the first rainfall-recharge relationship for the entire country (Figure 2.1). These values were derived from water balance estimates and low flow discharges from small river catchments.

Figure 2.1: Enslin's regional rainfall/recharge relationship for summer and winter rainfall regions of South Africa



(Source: Bredenkamp, et al. 1995)

2.4.2 Groundwater recharge maps

The Directorate of Geohydrology in DWAF has undertaken to produce 1 : 500 000 general hydrogeological maps which include 1 : 2 000 000 inset groundwater recharge potential maps. The recharge values used come from a compilation of various estimation methods. For example, equations 2.5 and 2.6 were used in the Queenstown map, and base flows and equation 2.2 were used in the Cape Town map (Baron, pers comm.). In the Pietersburg map, a rating system was developed which was calibrated against observed recharge estimates (Haulpt, pers comm.). The rating system was based on factors which affect recharge, like rainfall, topography, soils and depth of water table.

The Department of Agricultural Engineering, University of Natal, Pietermaritzburg, with support from the Water Research Commission, produced a net recharge map of South Africa based on the physical conceptual model, ACRU. The ACRU model considers moisture movement in the vertical dimension, and provides a means of estimating the amount of water leaving the root zone at a specific site. A major drawback with the model with respect to its application on a regional level, is that it was designed for use in areas where recharge occurs via porous media, and therefore it can not account for direct recharge via preferential pathways. As discussed earlier, flow via macro pores, joints, fissures and the like is believed to be of major significance in areas characterised by deep soils or a semi-arid climate (Lloyd, 1986; Sami, 1992; Kirchner et al. 1991; Rushton, 1987; Sharma and Hughes, 1985).

The Water Research Commission together with DWAF published a set of groundwater maps entitled "Groundwater Resources of South Africa" which include a 1 : 7 500 000 scale map of mean annual recharge values (Vegter, 1995). The recharge map, which should be viewed as depicting broad trends rather than accurate regional recharge figures, is based on base flow estimates, point studies that have employed a variety of estimation methods and effective rainfall from the ACRU model (Vegter, 1995). Effective rainfall is defined by Schultze et al. (1995) as rainfall, minus interception loss, minus storm flow for a given day. This map, while inheriting the drawbacks on which the point and regional recharge estimates were made, is a collation of a vast surface and groundwater data base, and is the most recent national scale recharge map. The map, henceforth referred to as the National Groundwater Map (NGM), also has relatively small recharge contour intervals (Table 2.2).

Table 2.2 Groundwater recharge maps: recharge classes in mm/a

	RECHARGE CLASSES (mm/a)					
DWAF's 1 : 2 000 000 recharge maps:						
Pietersburg:	<12	12-20	20-32	>32		
Cape Town:	0-5	5-10	10-50	50-100	>100	
Oudtshoorn & Port Elizabeth:	< 20	20-30	30-60	>60		
ACRU:	0-5	5-10	10-50	50-100	>100	
NGM:	0-1 37-50	1-5 50 - 75	5-10 75-110	10-15 110-160	15-25 160-200	25-37 >200

Table 2.2 shows that, apart from the National Groundwater Maps, the recharge contour intervals of local regional maps are too large for use in site specific studies. The use of regional maps appears to be limited to the depiction of qualitative trends rather than quantitative information.

2.5 A COMPARISON OF REGIONAL RECHARGE ESTIMATION METHODS

In this section regional recharge estimation methods are compared using the recharge values and ranges from Table 2.1. The aim of this comparison is to identify methods which will yield relatively conservative recharge values, as this researcher feels that an underestimation of the available groundwater resource is preferable in exploitation potential studies. With respect to rural communities in South Africa, the potential to upgrade a water supply scheme is far more desirable than a system which has failed due to the over-estimation of the water resource.

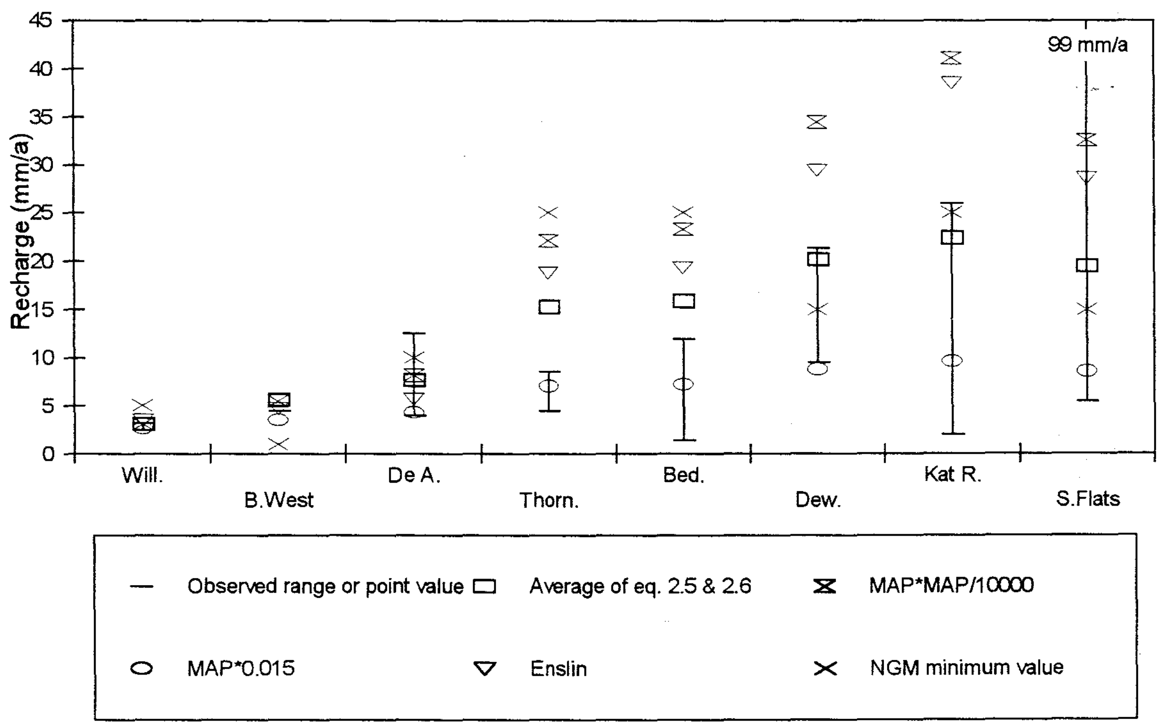
The following regional estimation methods out of those presented in section 2.4 are compared:

- $MAP^2/10\,000$
- Enslin's recharge values
- NGM minimum values
- Karoo aquifers: The average of Kirchner et al. (1991) equations 2.5 & 2.6
- Sedimentary in hard rock aquifers in mountainous catchments: $R = 0.73\ (P_{av} - 480)$ [mm]
- Dolomite aquifers: $R = 0.32\ (MAP - 360)$ [mm]

Karoo aquifers

The high recharge values obtained in Kok's (1992) spring flow study have been excluded in this comparison because the aim of this exercise is to identify relatively conservative regional recharge estimation methods. In order to do so, the regional estimation methods described in the previous section have been plotted against the observed recharge ranges (Figure 2.2), and another regional estimation method based on equation 2.2 has been introduced. This last method, where recharge is taken as 1.5% MAP, was obtained by inspecting the observed recharge ranges and selecting a percentage of MAP which generally gave a conservative recharge value. Figure 2.2 shows that where MAP is low (< 300 mm/a), all the methods give reasonable recharge values, although the NGM minimum values tend to be slightly high (Williston) or slightly low (Beaufort West). Where MAP is above 300 mm/a, 1.5 % MAP tends to give an acceptable, conservative value. This relationship may only be applicable where MAP is less than approximately 700 mm/a, since the maximum MAP in the cases presented is 641 mm/a (Kat River).

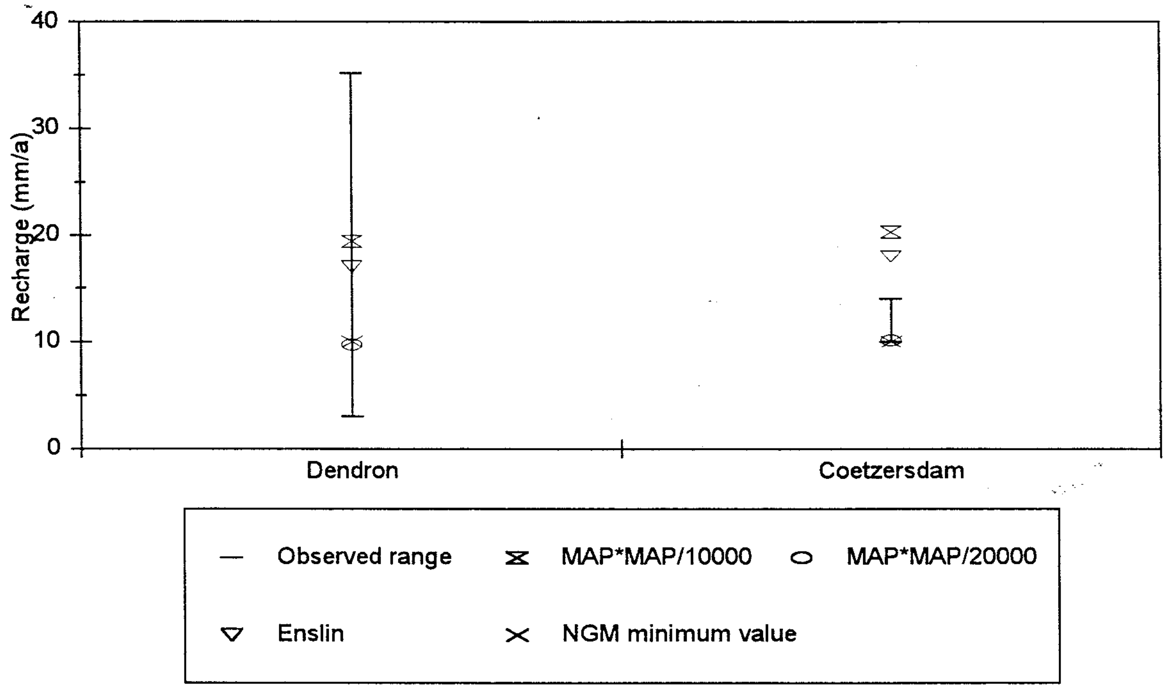
Figure 2.2 A comparison of regional recharge estimation methods: Karoo aquifers



Granitic aquifers

Figure 2.3 shows that out of the regional recharge estimation methods presented in section 2.4, the NGM minimum values are the only ones which fall within both the observed ranges. Equation 2.12 was modified to $(MAP)^2/20\ 000$ which produced conservative recharge values that fall within the observed ranges for the two aquifers.

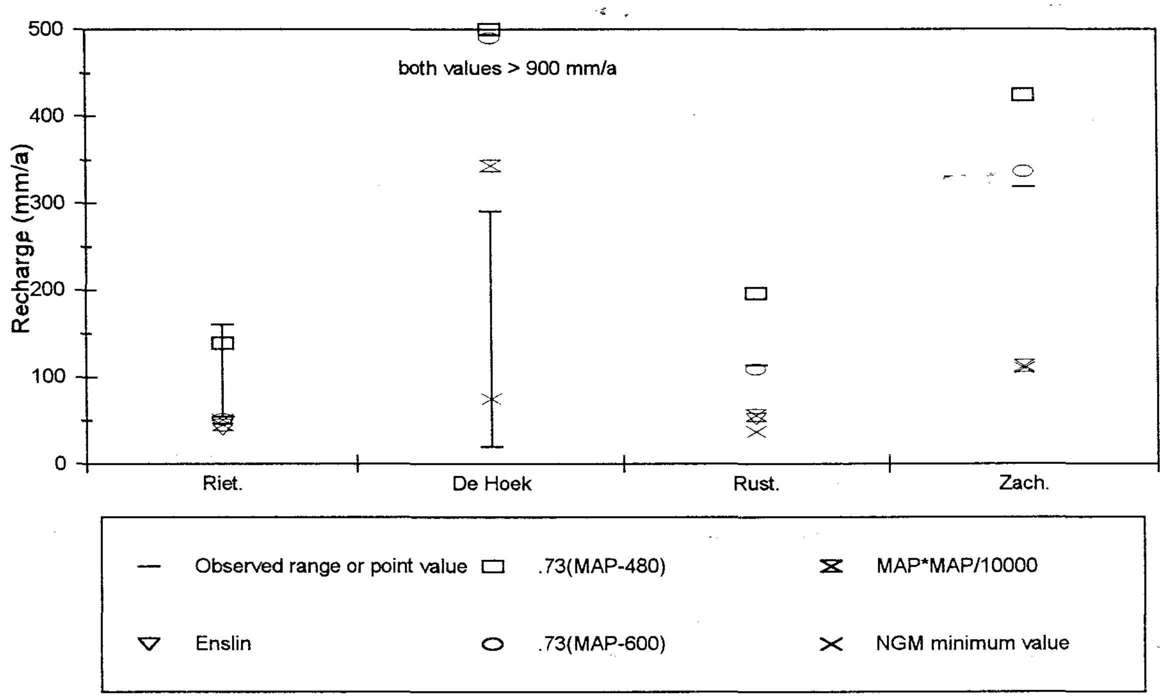
Figure 2.3 A comparison of regional recharge estimation methods: Granitic aquifers



Sedimentary aquifers in mountainous catchments

Recharge is unlikely to be the factor which limits an aquifer's exploitation potential in areas of high rainfall. Permeability is more likely to be limiting. For the purposes of this study, it is therefore not necessary to establish a regional recharge estimation method which gives acceptable values in high rainfall areas like De Hoek in the Drakensberg and Zachariashoek in the Western Cape. For the two areas with a MAP less than 800 mm/a, namely Rietondale and Rustenburg, the NGM minimum values, $MAP^2/10\ 000$ and Enslin's values give recharge rates which are possibly too conservative (Figure 2.4). Equation 2.9 (□ marker in Figure 2.4), while within the observed range in Rietondale, gives a value which is greater than the maximum observed value in Rustenburg. Equation 2.9 was modified 0.73(MAP-600), which not only gives a better fit for Rietondale and Rustenburg, but also for Zachariashoek which has a MAP in the region of 1 000 mm/a.

Figure 2.4 A comparison of regional recharge estimation methods: Sedimentary aquifers in mountainous catchments

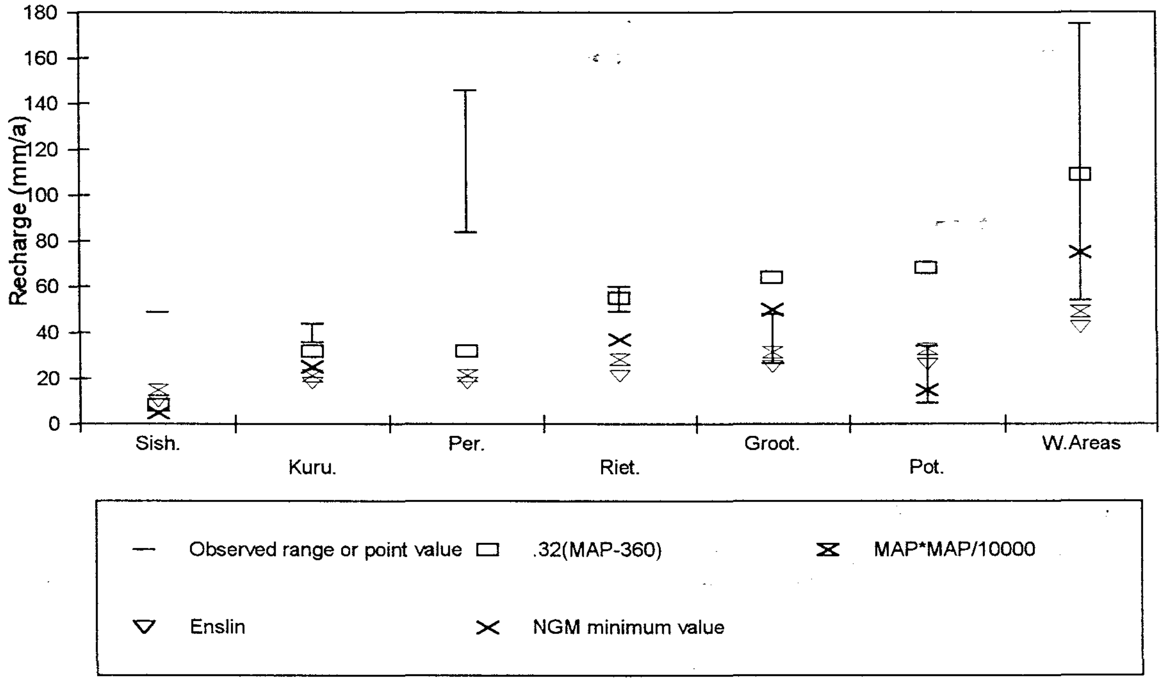


Dolomitic aquifers

Figure 2.5 shows that none of the methods presented give consistent, acceptably conservative recharge values in relation to the observed ranges. The NGM minimum values, $MAP^2/10\ 000$ and Enslin's values mostly fall below the observed recharge values, and may be too conservative to apply regionally. The recharge values obtained using equation 2.8 (□ marker in Figure 2.5) were generally higher than what the other methods gave, and in two cases this formula yielded values greater than the maximum observed value. It may not be possible to establish an acceptable regional recharge estimation method for dolomite aquifers because their ability to accept water differs so greatly. Dolomite aquifers obtain their permeability from chemical weathering, which differs in intensity between dolomitic formations and geographical areas.

Most of the recharge studies undertaken in South Africa have been on dolomitic aquifers. For this reason, it may be possible to obtain a useable value for a specific dolomite aquifer after considering established recharge values from nearby dolomitic aquifers.

Figure 2.5 A comparison of regional recharge estimation methods: Dolomitic aquifers



Kalahari/Karoo aquifers

These aquifers are located in the Northern Cape, North West Cape and Botswana. Three of the four examples in Table 2.1 gave recharge values which lie between 0.7 % - 1.0 % MAP, indicating that a regional, slightly conservative value could be taken as 0.8 % MAP. To consider recharge as a percentage of MAP may be acceptable for estimating an aquifer's exploitation potential, however recharge in the arid Kalahari should rather be viewed as episodic, when rare, exceptional rainfall events contribute to most of an aquifer's recharge (Verhagen, pers comm.).

3.6 CONCLUSIONS

The starting point for arriving at a recharge value to use in equation 2.1 should be to consult the two most recent, comprehensive studies on groundwater recharge in South Africa:

Bredenkamp,DB, Botha, LJ, Van Tonder, GJ, Janse van Rensburg, H. 1995. **Manual on quantitative estimation of groundwater recharge and storativity based on practical hydro-*logical* methods.** Water Research Commission Report No 353.

Connelly, RJ, Abrams, LJ, Schultz, CB. 1989. **An investigation into rainfall recharge to groundwater.** Water Research Commission Report No 149/1/89.

If the aquifer for which a recharge value is needed is not located in a similar recharge environment to the case studies described in these reports, then the following values could be used, bearing in mind that they are likely to be slightly conservative:

Karoo aquifers

R = 1.5% of MAP [mm] where MAP is less than 700 mm/a

Granitic aquifers

$R = (MAP)^2/20\ 000$ [mm]

Hard rock sedimentary aquifers in mountainous catchments

R = 0.73 (MAP - 600) [mm] where MAP is less than 1 100 mm

It was not possible to establish a suitable relationship for MAP values greater than 1 100 mm. In such areas recharge is unlikely to be the factor which limits the aquifer's exploitation potential.

Dolomitic aquifers

The recharge value should be obtained after considering established recharge values from nearby dolomitic aquifers.

Kalahari sand and shale aquifers

R = 0.8 % of MAP [mm]

3. A METHOD TO ESTIMATE THE ABSTRACTABLE PROPORTION OF RECHARGE FROM A SINGLE BOREHOLE

3.1 INTRODUCTION

This chapter presents a method of estimating the proportion of recharge that can be abstracted from single boreholes within relatively small catchments, of up to approximately 10 km^2. The reason for concentrating on small catchments is because recharge could be limiting when a small contributing area is available. This could be particularly relevant in cases where an aquifer with highly transmissive zones is supplied from a limited recharge area. In such a case the aquifer may not be able to consistently supply water to a high yielding borehole.

No previous research on this specific topic could be found. In a regional groundwater exploitation potential assessment, DWAF (1993) used 50% as the proportion of groundwater that can practically be abstracted by boreholes. While this value may be considered for regional planning purposes, a site specific value is of importance when assessing a single borehole's yield potential. The following site specific factors which could affect the percentage of recharge abstractable from a single borehole were taken into account:

- the width of the aquifer at the borehole site;
- the degree of anisotropy in the aquifer;
- recharge rates to the aquifer;
- the aquifer's transmissivity;
- the location of the borehole within the aquifer - whether the borehole penetrates a relatively high or low transmissive zone in the aquifer;
- the size of the aquifer.

3.2 METHODOLOGY

The method used involved the following process:

i) Hypothetical aquifers with different combinations of transmissivity distributions, anisotropies, areas, borehole positions, recharge values and widths over which outflow from the aquifer can take place (seepage face) were simulated to establish the percentage of recharge that a single borehole can abstract. The finite difference groundwater simulation model, MODFLOW was used.

ii) A formula to describe the relationship between recharge and abstractable percentage of recharge for the various aquifer configurations that were modelled was established.

iii) A general method to obtain empirical parameter values to be used in the formula was developed.

3.2.1 The groundwater simulation model - MODFLOW

MODFLOW is a sophisticated, block-centred finite difference model capable of simulating unconfined, confined, leaky and mixed or convertible aquifer systems in either steady or transient states. The model was developed by the United States Geological Survey (McDonald and Harbaugh, 1988) and is probably the most successful and widely used groundwater model in existence. The model simulates groundwater flow three dimensionally using a sequence of layers of porous material, each characterised by its own thickness and hydraulic parameters. These properties can be varied across the model grid. Flow associated with external stresses, such as wells and boreholes, recharge, evapotranspiration from shallow water tables, springs, streams and permeable or impermeable boundaries can also be simulated. Several iterative techniques are available to solve the groundwater flow algorithms.

To adapt any porous media model to the fracture rock conditions commonly encountered in South Africa requires that several assumptions be made regarding the conceptualisation of the flow regime. Fractured systems are typically modelled using one of the following conceptual models: equivalent porous medium (EPM); discrete fractures; dual porosity. Most modelling studies use the EPM approach. In this approach, the primary and secondary porosity and hydraulic conductivity distributions of the fractured material are replaced by a continuous porous medium having equivalent effective hydraulic properties. It is therefore assumed that the fractured material can be treated as a continuum and that a representative elementary volume (REV) of material characterised by effective hydraulic parameters can be defined. The difficulty in applying the EPM approach arises in determining the appropriate size of the REV required to define average equivalent hydraulic properties. There is an on going debate as to whether REV's exist for fracture rocks. Some researchers have suggested that the EPM approach may not be valid for fracture systems, especially those where fractures are few and far between. However, they also note that although the EPM approach may poorly reproduce local conditions, it adequately represents the behaviour of regional flow systems. Consequently, in rocks where the fracture pattern is of a regional nature, variations in transmissivity resulting from differences in the hydraulic conductivity of individual fractures and from different localised fracture densities can presumably be reduced if a sufficiently large grid size is employed.

3.2.2 The simulated aquifers

The size of the aquifers used in this exercise were approximately 1 km^2 and 5 km^2 and the widths across which outflow can occur (seepage faces) were set at 200 m, 400 m and 1000 m for the 1 km^2 aquifers, and 1000 m, 2000 m and 3000 m for the 5 km^2 aquifers. This meant changing the length of the aquifers in order to keep the areas constant in each simulation with a different seepage face. The aquifers were treated as a single confined layer in a steady state condition. A telescopic grid size was adapted in the vicinity of the pumping borehole since finite difference models average the water levels over the entire grid cell. The area of the grid in which the borehole was located was set as 10 m^2. Grid size was then expanded outwards in both directions by a factor of 1.5 to 2. Such a low expansion factor minimises the error in the second derivative of the finite difference expression.

The aquifers were divided into two transmissivity zones, termed Tmax for the high transmissivity zone and Tmin for the low transmissivity zone. The Tmax zone should be viewed as the intensely fractured or weathered part of the aquifer, representing for example a linear shaped fracture zone. The Tmin zone should be seen as the average transmissivity of the aquifer. The width of the central Tmax zone was set at 40 m and the widths of the Tmin zones on either side of the Tmax zone were determined by the remaining width of the seepage face. The model was run with the borehole in both the Tmax and the Tmin zones. Examples of the grids are shown in Figures 3.1 and 3.2.

The transmissivity values used were:

Tmax zone (m^2/day)	Tmin zone (m^2/day)
5	2.5
10	5
20	10
50	25
50	5
50	10
50	15
200	5
200	10
200	15

These transmissivity values were selected based on personal experience and a review of literature on secondary aquifers, to identify likely ranges of transmissivity values. Although lower transmissivity values than 5 m^2/day and 2.5 m^2/day are commonly found in South Africa, aquifers with transmissivity values less than these were not modelled because boreholes which penetrate such aquifers are commonly 'handpump' boreholes, and have very limited production potential.

In order to account for the different degrees of anisotropy in permeability found in South African fractured aquifers, the model was run with anisotropy values of 0.1, 0.5 and 1.0. An anisotropy value of 0.1 represents a highly linear flow system where transmissivity along the length of the aquifer (x-axis) is ten times the transmissivity along the aquifer's y-axis. An anisotropy value of 0.5 indicates that permeability along the x-axis is twice that along the y-axis. This represents a system where there is a preferred fracture orientation in an environment with secondary fractures. An anisotropy value of 1.0 (ie. isotropic) assumes an equal fracture pattern in the x and y directions and is equivalent to a porous medium.

Recharge from precipitation was assumed to be evenly distributed over the aquifer. Although this may not be physically correct, the location of the borehole near the aquifer outlet allows for any local variations in head that may result from local variations in recharge to be redistributed before reaching the borehole. Recharge from rivers was not simulated because conditions over much of the country mitigate against rivers being all but minor, localised sources of recharge (Vegter, 1995).

Outflow from the aquifer was simulated using a head-dependant flow boundary which allows water to flow out of the aquifer until the piezometric surface falls below a specific level. This level was set to the elevation of the water strike in the pumping borehole. These boundaries were set 1 km away from the borehole in the down gradient direction when the borehole was located in the Tmax zone of the aquifer, and 350 m from the borehole when the borehole was located in the Tmin area of the aquifer. It was assumed that this was the maximum downflow distance from which the borehole could draw water by gradient reversal arising from pumping.

Flow across the boundary is dependent on the head in the adjacent model cell and a user defined boundary conductance value. Conductance values were determined from presumed cell throughflow using Darcy's Law based on cell size, transmissivity and a hydraulic gradient of 0.01. The maximum recharge to a given configuration was limited to that which resulted in unrealistic hydraulic gradients in the central portion of the aquifer. The maximum hydraulic gradient that was accepted was 0.02.

A maximum abstraction value was defined as the point at which drawdown reaches the water strike. This drawdown level was chosen from a physical point of view because abstraction should avoid dewatering fractures. From a modelling point of view it avoids the transition to unconfined flow. It also avoids the situation in fractured rock aquifers where increasing drawdown below the water strike does not increase the hydraulic gradient towards the borehole and therefore does not increase the groundwater flow to the borehole. The model cannot handle this situation as it assumes that the gradient continues to increase with increasing drawdown.

One problem encountered was when very low recharge values were used (for example, 1 mm/annum) with relatively high transmissivity values (for example 50 m^2/day). In such cases the water table is relatively flat and therefore it is not possible to abstract any significant amount of the recharge without dropping water levels below the water strike. As a result the maximum permissible abstraction rate was generally underestimated. In addition, in these cases small variations in abstraction rates correspond to large variations in the fraction of recharge abstracted, consequently large deviations in the exploitation potential may result. For these reasons, the exploitation potential at very low recharge values were in some cases disregarded.

3.3 RESULTS

The results of the modelling exercise are presented in graphical form in Appendix 1.

3.3.1 Generalisations

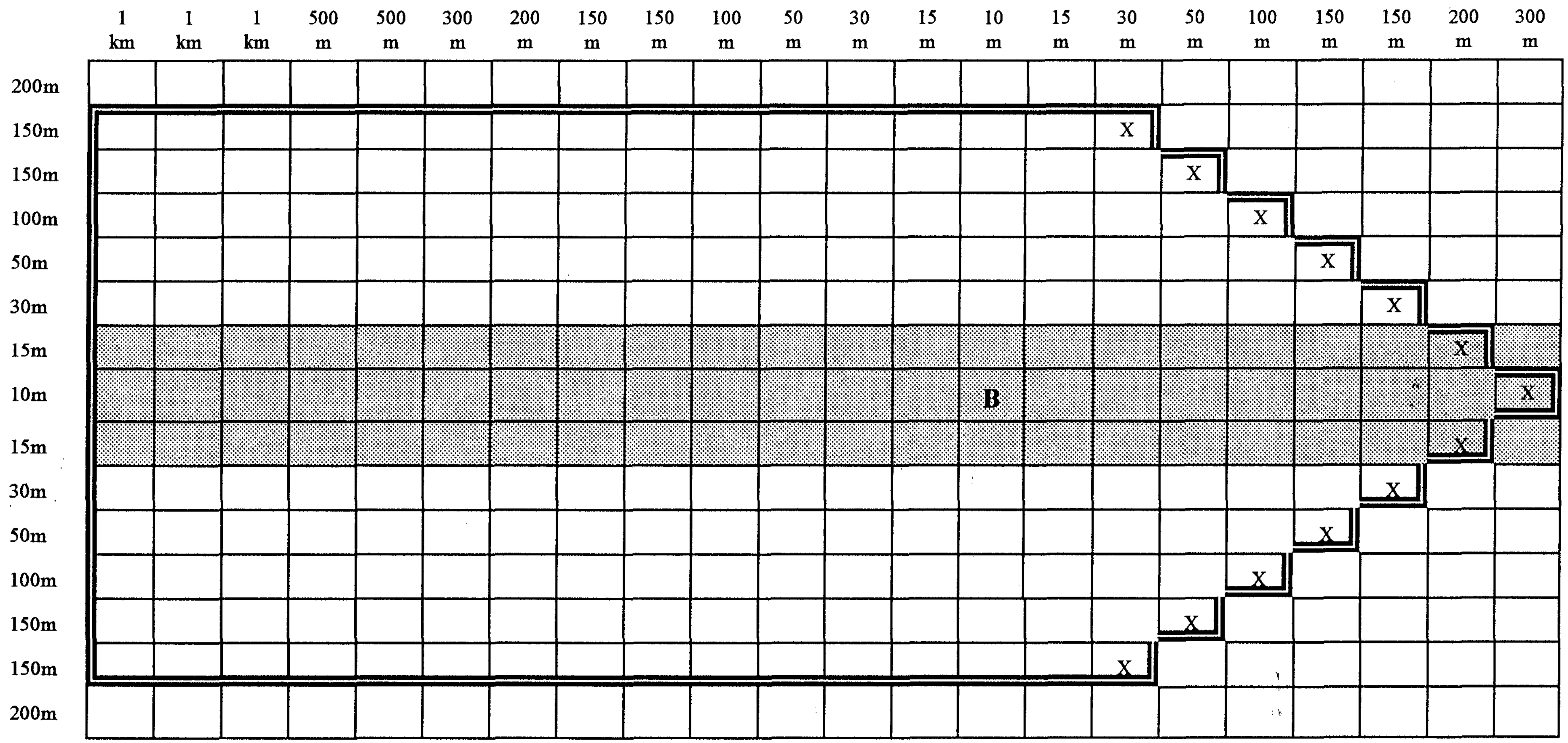
The following generalisations can be made:

The abstractable percentage of recharge:

- increases as the seepage face decreases;
- increases as isotropy increases;
- increases or remains the same as recharge decreases;
- increases or remains the same as the transmissivity of the high and low transmissive zones increases;
- increases as the transmissivity ratio between the high and low transmissive zones increases;
- increases when the borehole is located in the most transmissive zone of the aquifer.

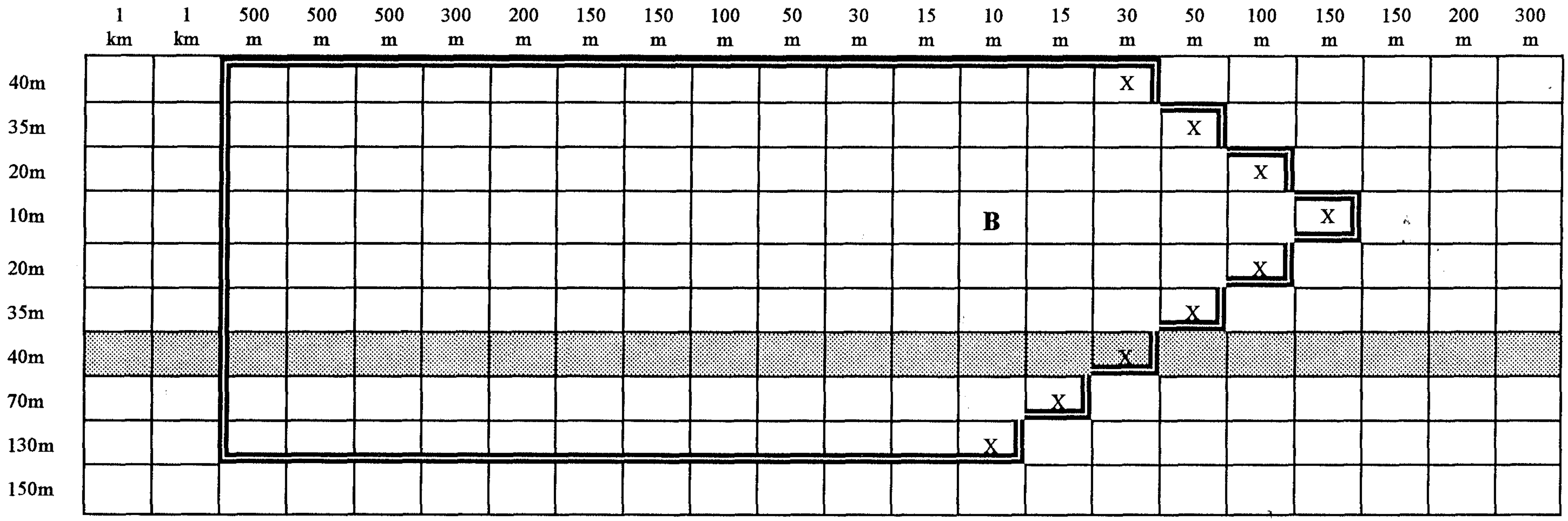
A change in the recharge area was found to have little effect on the abstractable percentage of recharge. The only exception was when high transmissivity values (200 m^2/day) and high transmissivity ratios (greater than ten times) were used. In these circumstances, and with anisotropies of 0.1 the differences between the abstractable percentage of recharge in 1 km^2 and 5 km^2 catchments were found to be as high as 20%. These differences were generally found to be less than 10% with anisotropies of 1.0.

Figure 3.1 An example of the simulated aquifer with the borehole located in the high transmissivity zone: the grid used for a ±5 km² recharge area and a seepage face of 1000 m



The hatched portion represents the high transmissivity area, 'B' marks the borehole cell and 'X' marks the outflow boundary cells.

Figure 3.2 **An example of the simulated aquifer with the borehole located in the low transmissivity zone: the grid used for a ±1 km² area and a seepage face of 400 m**



The hatched portion represents the high transmissivity area, 'B' marks the borehole cell and 'X' marks the outflow boundary cells.

3.3.2 The governing formula

The following formula describes the shape of the recharge versus abstractable proportion of recharge curves:

$$D = (a\,R^{-0.7} + c)f \qquad \text{eq.3.1}$$

where:

D = abstractable proportion of recharge (%)
R = recharge to the aquifer (mm/year)
a and c are variables
f is a multiplication factor related to the Tmax/Tmin ratio

A step by step process of how to obtain 'a', 'c' and 'f' values for site specific conditions is outlined in section 3.3.3.

The following process was used to develop equation 3.1, the 'a' and 'c' graphs, and the 'factor' graphs:

Step 1: Establish the formula $D = (a\,R^{-0.7} + c)f$

1. The shape of the curves in Appendix 1 can generally be represented by an algorithm of the form: $y = (a\,x^{-b} + c)f$
2. Through curve matching, 0.7 was found to be an acceptable constant for the 'b' value. This represents the decrease in the abstractable proportion of recharge against recharge.
3. Values for 'a' and 'c' for the curves in Appendix 1 using a 'b' value of 0.7 were obtained through curve matching. It was found that the 'a' value is related to the width of the seepage face, anisotropy, transmissivity and whether the borehole is located in the Tmax or Tmin zone of the aquifer, and that the 'c' value is related to all of the above except that transmissivity was found to have little impact on the 'c' value. The 'a' and 'c' values obtained using a 'b' value of 0.7 for each simulated aquifer are presented in Appendix 2.
4. A multiplication factor (f) was found to be necessary when the ratio of Tmax to Tmin was greater than two. Where Tmax is twice Tmin the 'f' value is one.

Step 2: Generate the 'c' graphs - Figure 3.5

The 'c' graphs relate 'c' values to seepage face widths and anisotropies. They were developed in the following manner:

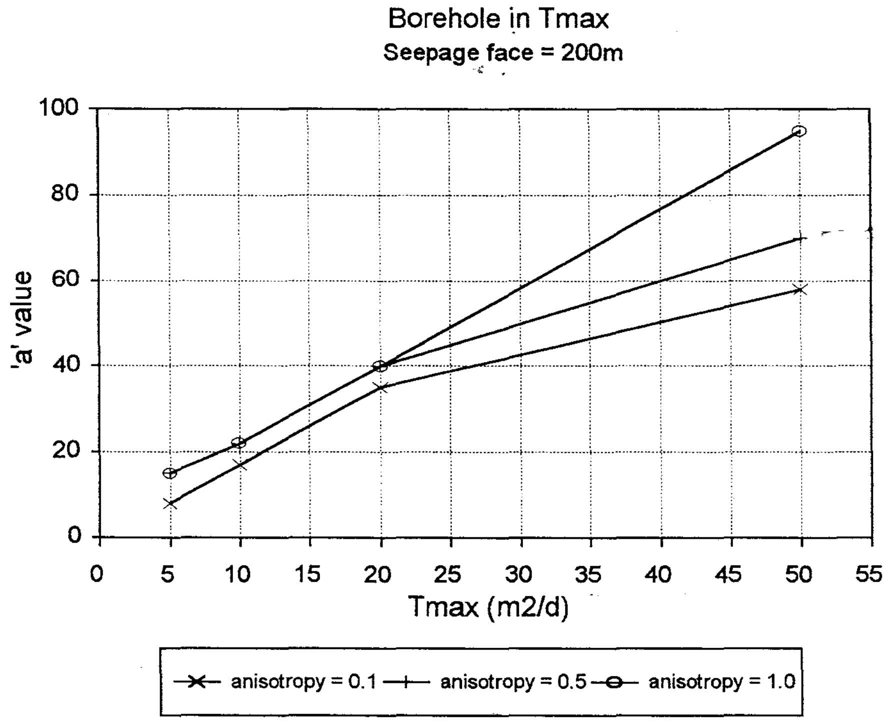
The 'c' values obtained in Step 1 for the cases where Tmax equals twice Tmin, were plotted against seepage face. The 'c' values are listed in Appendix 2.

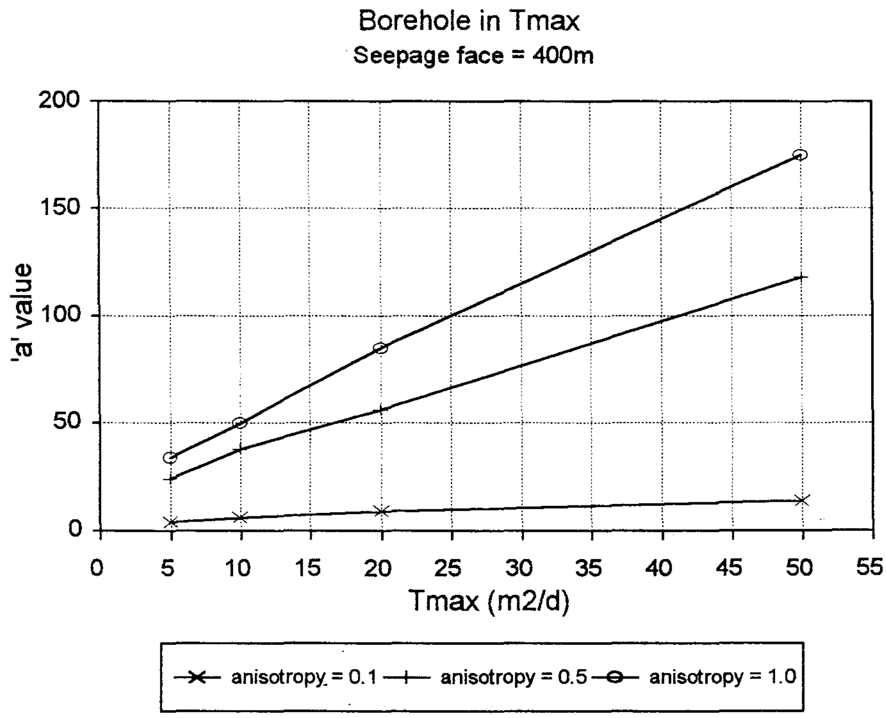
Step 3: Generate the 'a' graphs - Figure 3.4

The 'a' graphs relate 'a' values to seepage face widths for specific transmissivities and anisotropies. They were developed in the following manner:

1. Tmax (where Tmax is twice Tmin) was plotted against 'a' values obtained in Step 1 for seepage faces of 200 m, 400 m and 1000 m, and anisotropies of 0.1, 0.5 and 1.0. The 'a' values used are listed in Appendix 2. Figure 3.3 shows examples of such graphs.
2. The 'a' graphs (Figure 3.4) were generated using the 'a' values obtained from Figure 3.3, by plotting the 'a' value against seepage face for different Tmax values.
3. The peak of the 'a' graphs (Figure 3.4) for anisotropies of 0.5 and 1.0 needed to be established. Out of the seepage face widths used in the model, the 'a' values obtained in Step 1 for anisotropies of 0.5 and 1.0 generally appeared to peak at widths of 400 m and decrease to zero at 1000 m. It was necessary to establish whether the 'a' value peak was not somewhere between 400 m and 1000 m, or even at 300 m. This was done using equation 3.1 with seepage face widths of 300 m, 600 m, and 800 m, and comparing the results with expected values from the model. For example, if the model gave an abstractable proportion of recharge value of 90% for a seepage face of 200 m, and 80% for a seepage face of 400 m, it was assumed that the value for 300m should lie between 80% and 90%. In this iterative process using equation 3.1, the 'c' values were obtained from the 'c' graphs (Figure 3.5) and different 'a' values were used until a reasonable abstractable proportion of recharge value was obtained. It was found that the 'a' values peaked at a seepage face width of 400 m, and a straight line could be drawn between the 400 m seepage face 'a' value and the 1000 m seepage face 'a' value.

Figure 3.3 Examples of 'a' vs Tmax





Step 4: Establish the factor 'f' in the formula $D = (a\ R^{-0.7} + c)f$, and generate the factor graphs - Figure 3.6

The model described in section 3.2.2 was run with transmissivity ratios greater than two (between the high and low transmissivity zones), for seepage face widths of 200 m, 400 m and 1000 m. The results showed that the abstractable proportion of recharge increases as the transmissivity ratio between the high and low transmissive zones increases. Where Tmax is twice Tmin, the 'f' value in equation 3.1 is one. However, where Tmax is greater than twice Tmin, values for 'f' which are greater than one needed to be developed. The following steps outline the process of developing the 'f' values and the factor graphs:

1. Modelled abstractable proportion of recharge values obtained where Tmax is greater than twice Tmin (Table 3.1, column 2) were compared to values obtained from the formula where Tmax is twice Tmin, that is, where f = 1 (Table 3.1, column 3).
2. The multiplication factor needed for the formula value to match the modelled value was established (Table 3.1, column 4).
3. An acceptable single multiplication factor applied to the abstractable proportion of recharge where Tmax is twice Tmin was established by curve matching (Table 3.1, column 5).
4. The factor graphs (Figure 3.6) were then generated by plotting the multiplication factor vs seepage face for different anisotropies.

Table 3.1: An example of how the 'f' value in equation 3.1 was obtained

Recharge (mm/a)	Modelled value: Tmax > 2Tmin (% recharge)	Formula value: Tmax = 2Tmin (% recharge)	Multiplication factor (f)	Formula value x suitable 'f' value
Example 1: Seepage face = 1000 m, Tmax/Tmin = 10, Anisotropy = 0.5				
				f = 1.98
1	46	21	2.19	41.58
5	42	21	2.00	41.58
10	42	21	2.00	41.58
15	42	21	2.00	41.58
20	42	21	2.00	41.58
30	41	21	1.95	41.58
50	41	21	1.95	41.58
Example 2: Seepage face = 400 m, Tmax/Tmin = 3.3, Anisotropy = 0.1				
				f = 1.19
1	58	55	1.05	65.45
5	51	42	1.21	49.98
10	51	41	1.24	48.79
15	50	41	1.22	48.79
20	49	41	1.20	48.79
30	49	41	1.20	48.79
50	49	40	1.23	47.60

3.3.3 Using the governing formula to determine the abstractable percentage of recharge

The following steps outline the process of establishing the abstractable percentage of recharge from a single borehole:

A. **If Tmax = 2Tmin** (ie. where the highly transmissive zone of the aquifer is twice the lesser transmissive zone)

Step 1
Establish the following:

- Tmax from test pumping the borehole if it is located in the high T area; or from typical regional high T values if the borehole is located in the low T area.
- Tmin from test pumping other boreholes within the aquifer or from typical regional T values if the borehole is located in the high T area; or from test pumping if the borehole is located in the low T area.
- Seepage face at the borehole from geological mapping, air photos, topographical maps and geological maps. In many cases the width of the seepage face is likely to be similar to the width of the valley bottom.
- Anisotropy of the aquifer (see Section 3.4)
- Recharge for the area in which the borehole is located (see Chapter 2).

Step 2
Read off the 'a' value from the appropriate 'a graphs' in Figure 3.4. There are two sets of graphs, one set for when the borehole is located in Tmax and one set for when the borehole is located in Tmin.

Step 3
Read off the 'c' value from the appropriate 'c graph' in Figure 3.5. There are two graphs, one for when the borehole is located in Tmax and one for when the borehole is located in Tmin.

Step 4
Enter 'a', 'c' and the aquifer recharge value into equation 3.1 to obtain the abstractable proportion of recharge. Note that where Tmax is twice Tmin, the 'f' value is one.

B. **If Tmax is greater than 2Tmin** (ie. where the highly transmissive zone of the aquifer is more than twice the lesser transmissive zone)

Step 1
Go through steps 1 - 3 in A using the Tmax value. For example, if Tmax = 50 m^2/day and Tmin is 5 m^2/day, obtain a D value using T = 50 m^2/day.

Step 2
Obtain the 'f' value from the 'factor graphs' in Figure 3.6.

Step 3
Enter 'a', 'c', 'f' and the aquifer recharge value into equation 3.1 to obtain the abstractable proportion of recharge.

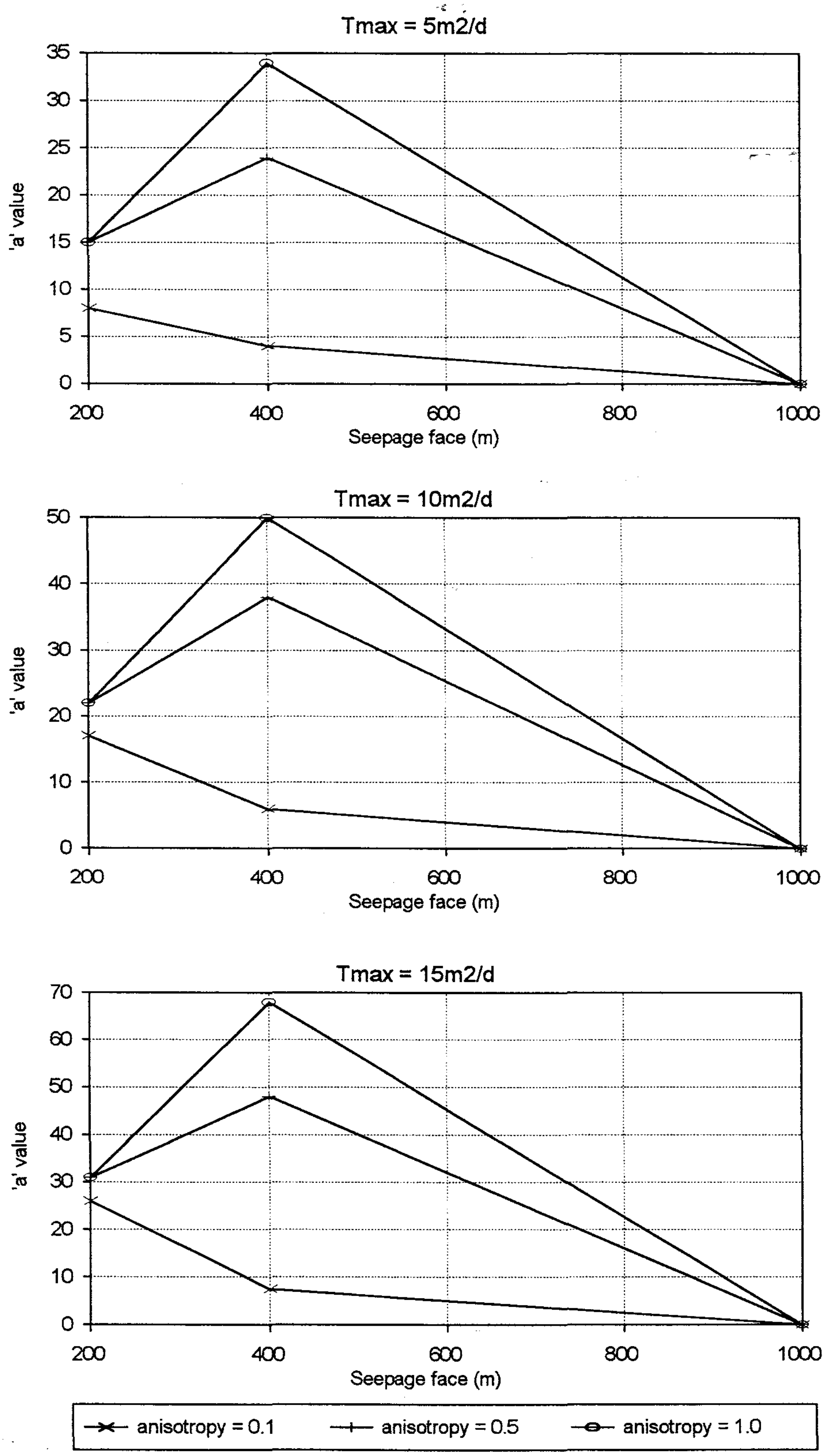
An example problem

Calculate the exploitation potential of a borehole located in the high transmissivity zone of a small 1 km^2 headwater catchment given that: recharge = 5 mm/year; the seepage face for the aquifer outflow is 400 m across the valley bottom; groundwater flow occurs along a highly transmissive (T = 50 m^2/day) dyke related fracture zone which is located in a low transmissivity (T = 5 m^2/day) country rock.

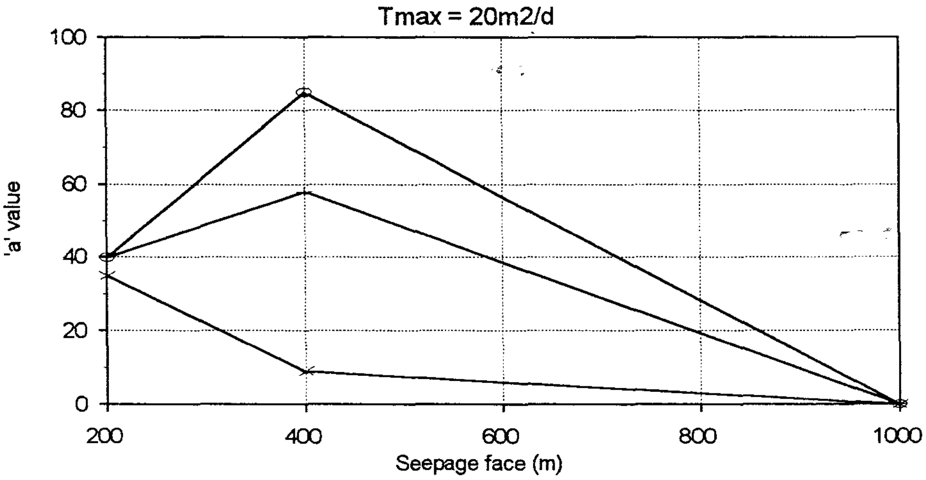
Select the 'a' graph for Tmax = 50 m^2/day and assume an anisotropy of 0.1 due to the highly linear transmissivity pattern. An 'a' value of 17.5 is obtained using Figure 3.4 and a 'c' value of 39 is obtained using Figure 3.5. Using equation 3.1 we get D = 45% of recharge. Since Tmax is ten times Tmin we must correct this value using the appropriate 'factor' graph. For a T ratio of ten, the multiplication factor is 1.67. Consequently, 45% multiplied by 1.67 gives an exploitation potential of 75% of recharge, which equates to an abstractable volume of 3 750 m^3/a.

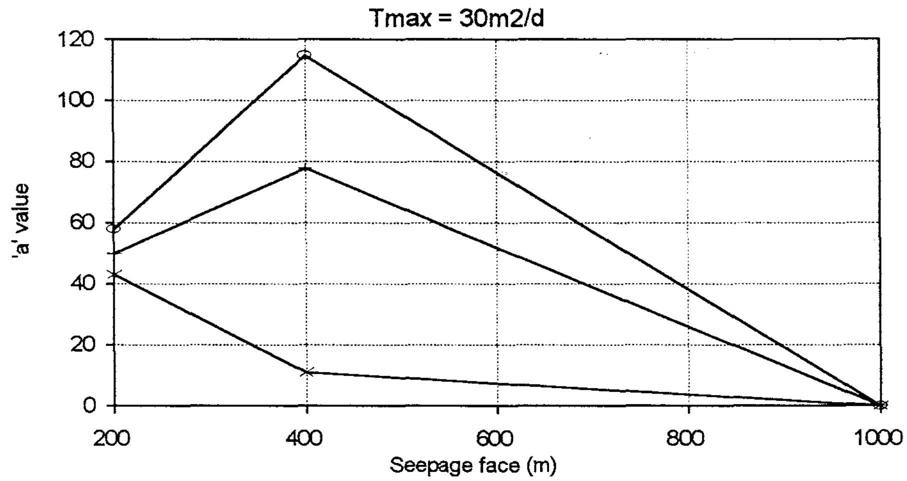
Figure 3.4 The 'a' graphs

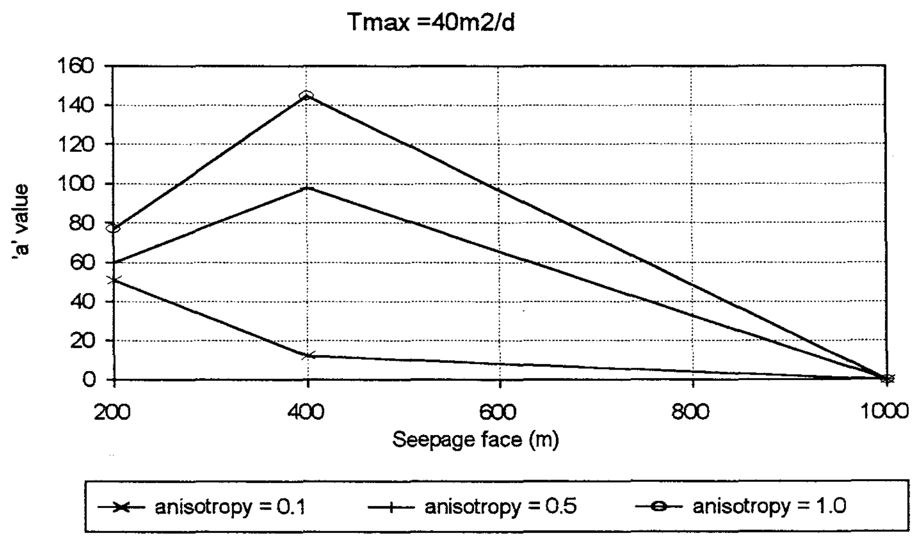
BOREHOLE IN Tmax



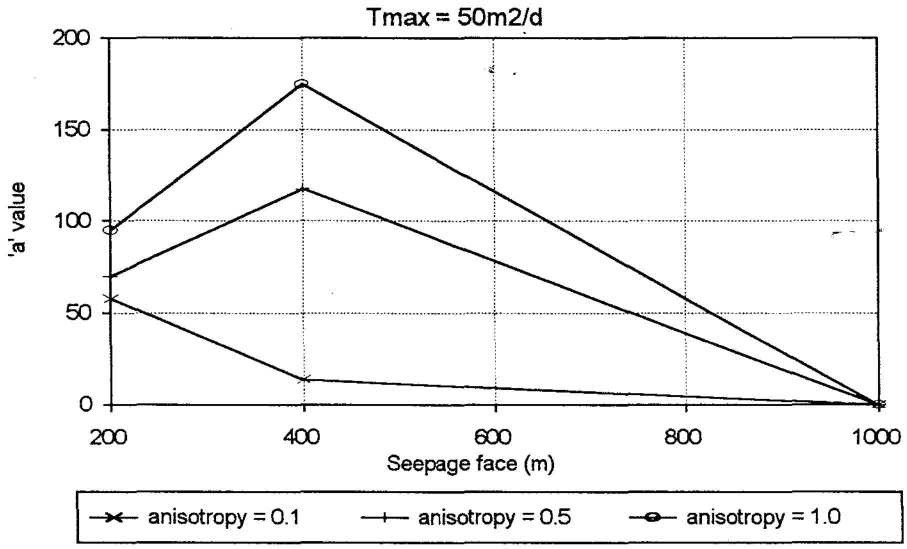
BOREHOLE IN Tmax



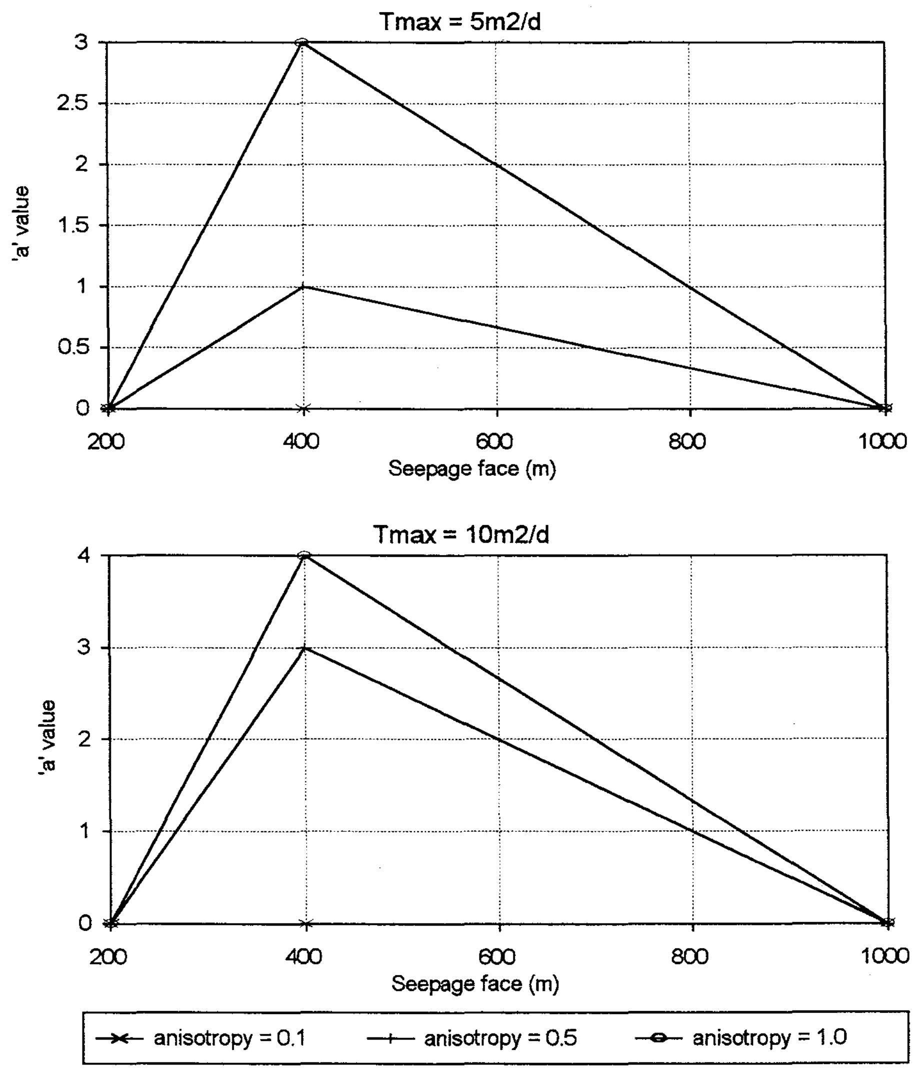




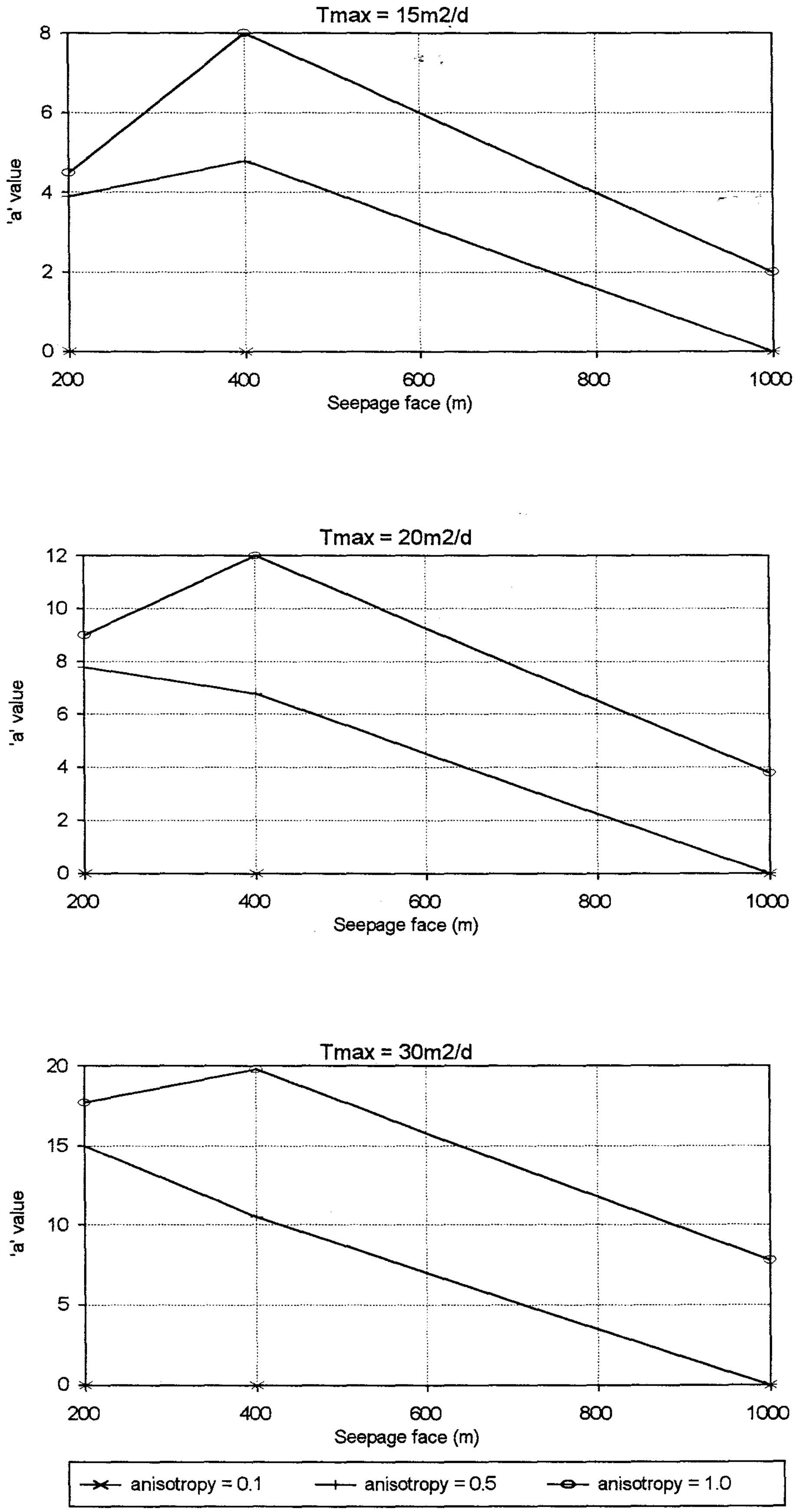
BOREHOLE IN Tmax



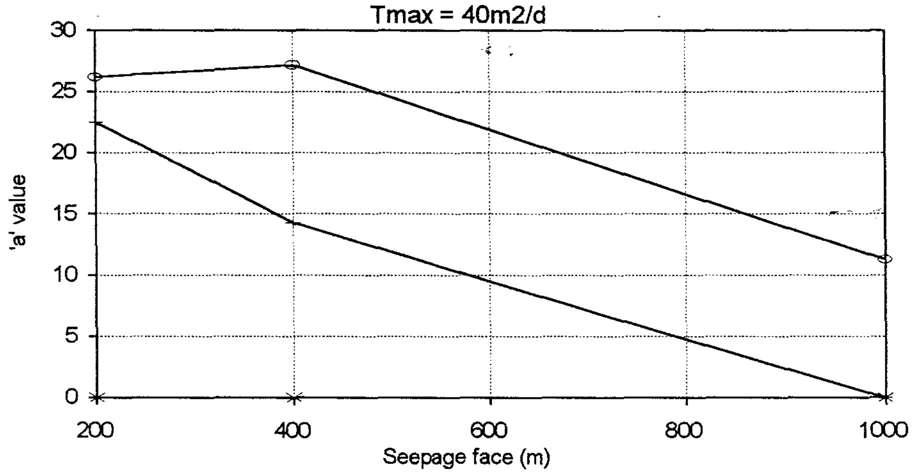
BOREHOLE IN Tmin



BOREHOLE IN Tmin



BOREHOLE IN Tmin



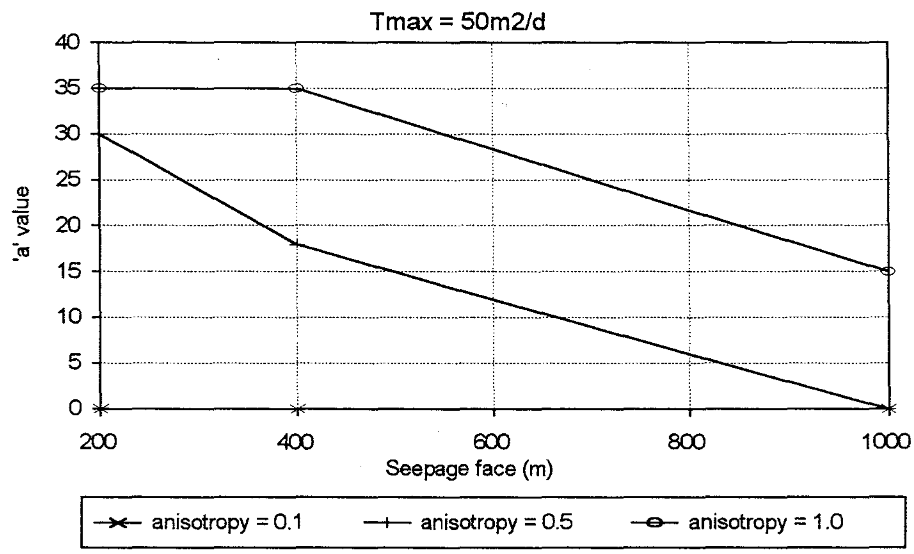
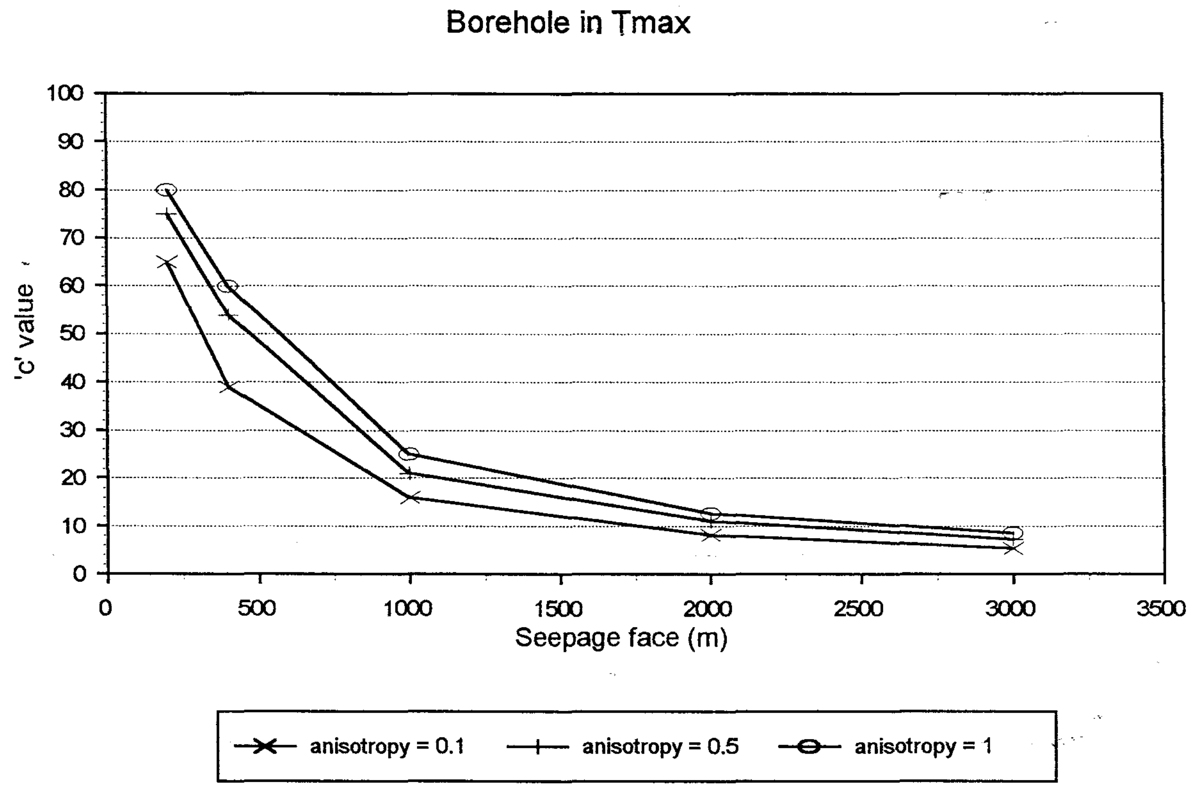


Figure 3.5 The 'c' graphs



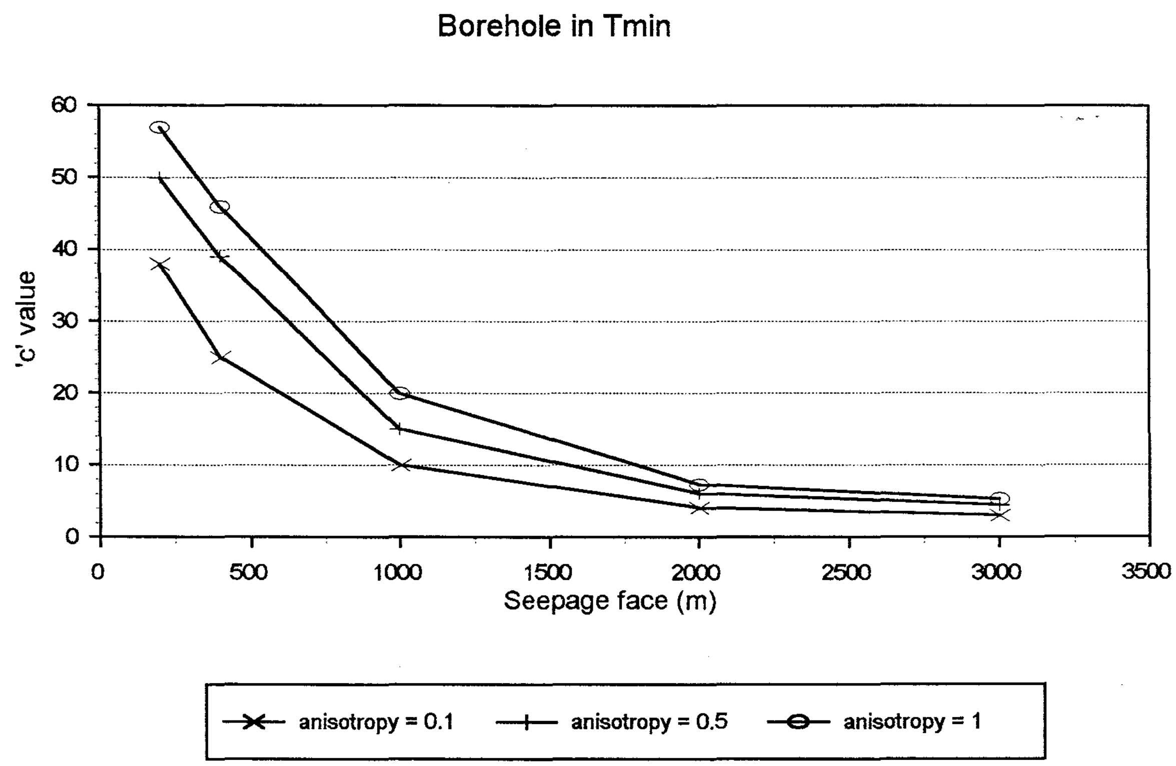
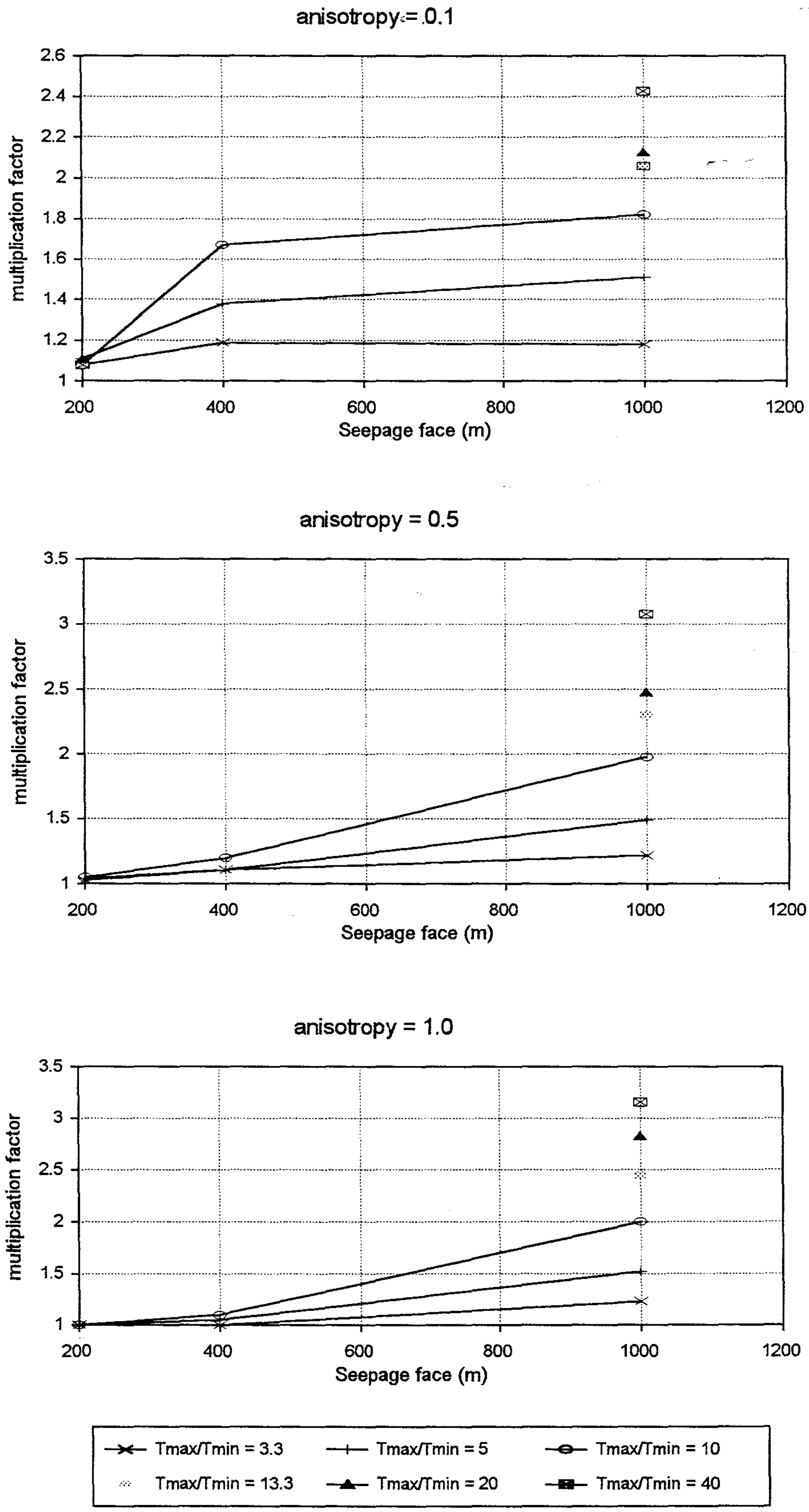


Figure 3.6 The factor graphs



3.3.4 Verification of the abstractable proportion of recharge formula (eq. 3.1)

Verification of equation 3.1 requires: i) that the formula gives results which fit the model data, and ii) that the formula fits field results. In order to test the first point, abstractable proportion of recharge values obtained from the model have been compared to the values obtained using equation 3.1 with the 'a' and 'c' values listed in Appendix 2. The results are presented in the four graphs making up Figure 3.7. These graphs indicate that the abstractable proportion of recharge obtained from the formula suitably match the values obtained from the model, although significant differences may arise when low recharge values are used. These discrepancies are a result of the model sensitivities at low recharge values (section 3.2.2).

The most noticeable differences occur in the cases where the Tmax/Tmin ratio is greater than ten. The model was run for Tmax/Tmin ratios of 13.3 times, 20 times and 40 times with a seepage face of 1000 m. Under these circumstances the results obtained using equation 3.1 together with the appropriate multiplication factor were lower than the results obtained from the model when the following values were used:

i) an anisotropy of 0.1 and a recharge of less than 5 mm/year
ii) an anisotropy of 0.5 and a recharge of less than 10 mm/year
iii) an anisotropy of 1.0 and a recharge of less than 15 mm/year.

The following points should also be observed when applying this method:

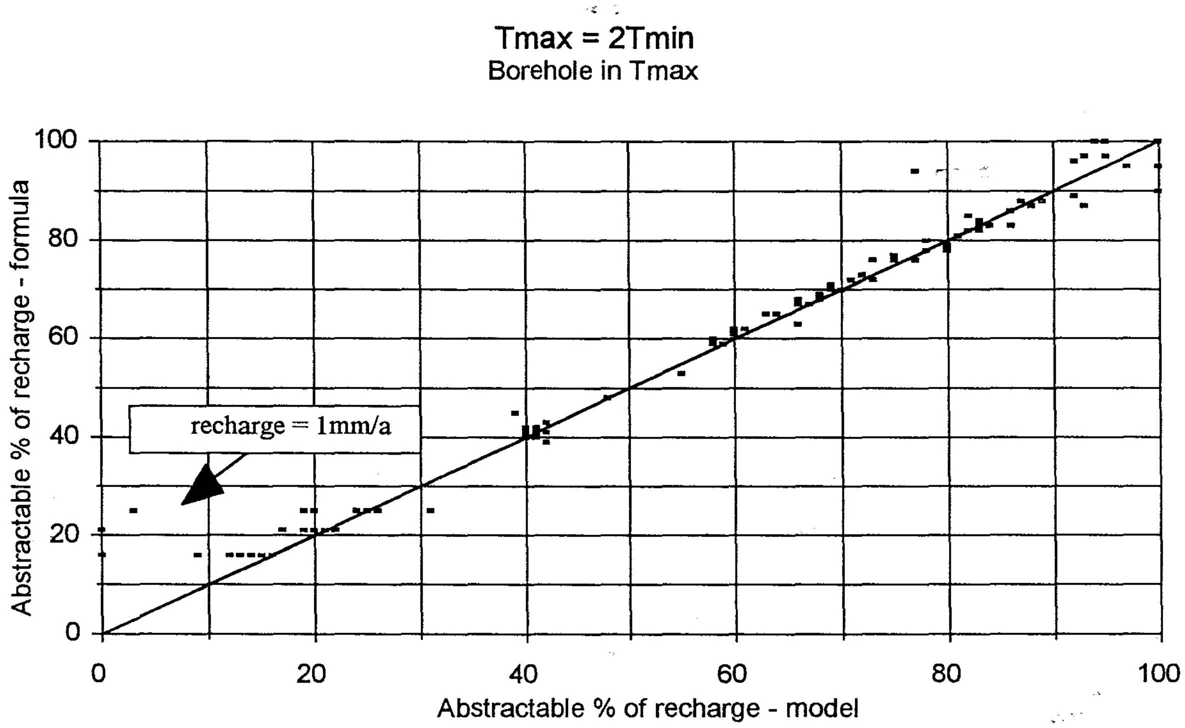
- If an abstractable proportion of recharge value of greater than 100% is obtained, then a figure of 100% should be assumed. This may occur when the seepage face is small (less than about 400 m) or the recharge value is small (less than about 5 mm/year), due to the generalisations of the recharge curves represented by equation 3.1.

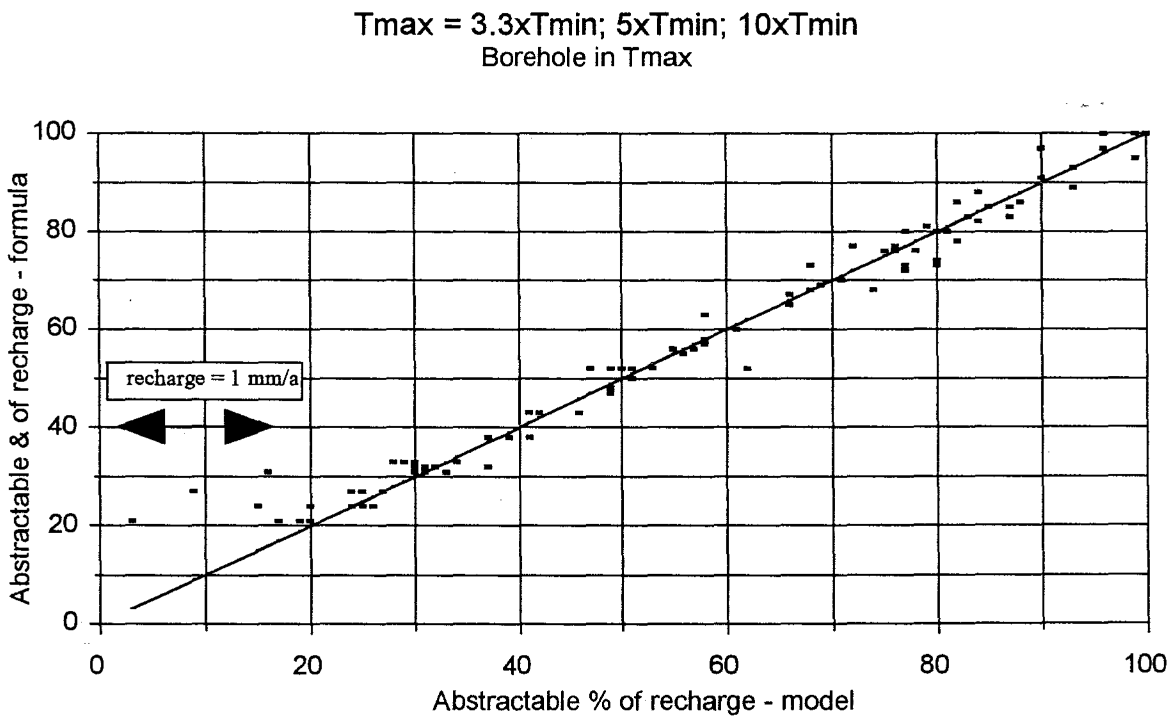
- The multiplication factors shown in Figure 3.6 were developed from the cases where the borehole was in the Tmax zone of the aquifer. Although similar factors may apply to cases where the borehole is in the Tmin zone of the aquifer, the existing 'factor graphs' cannot be assumed to represent such cases.

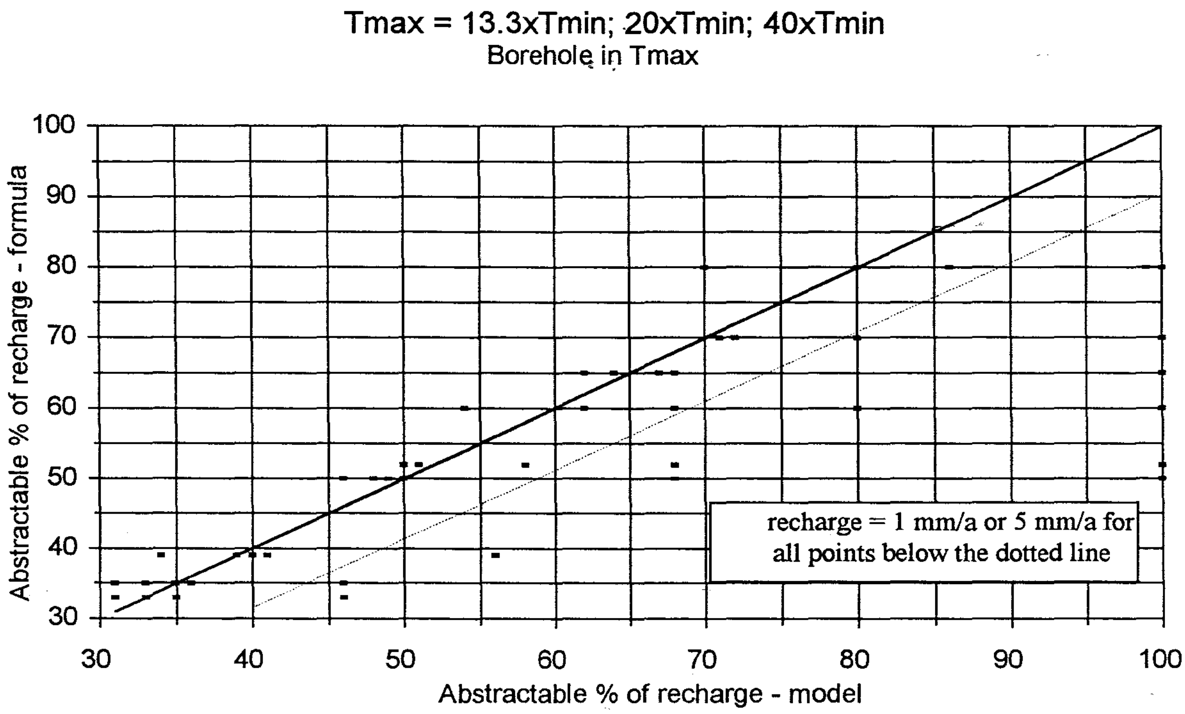
An attempt to verify this method with field data proved to be difficult. Only three case studies could be identified where a borehole is located in a clearly defined recharge contributing area, and where sufficient information exists to estimate the borehole's sustainable yield. The three examples (presented below) show that the formula can give acceptable results, considering that the production yields of the boreholes are either less than or close to their sustainable yields (Chapter 7).

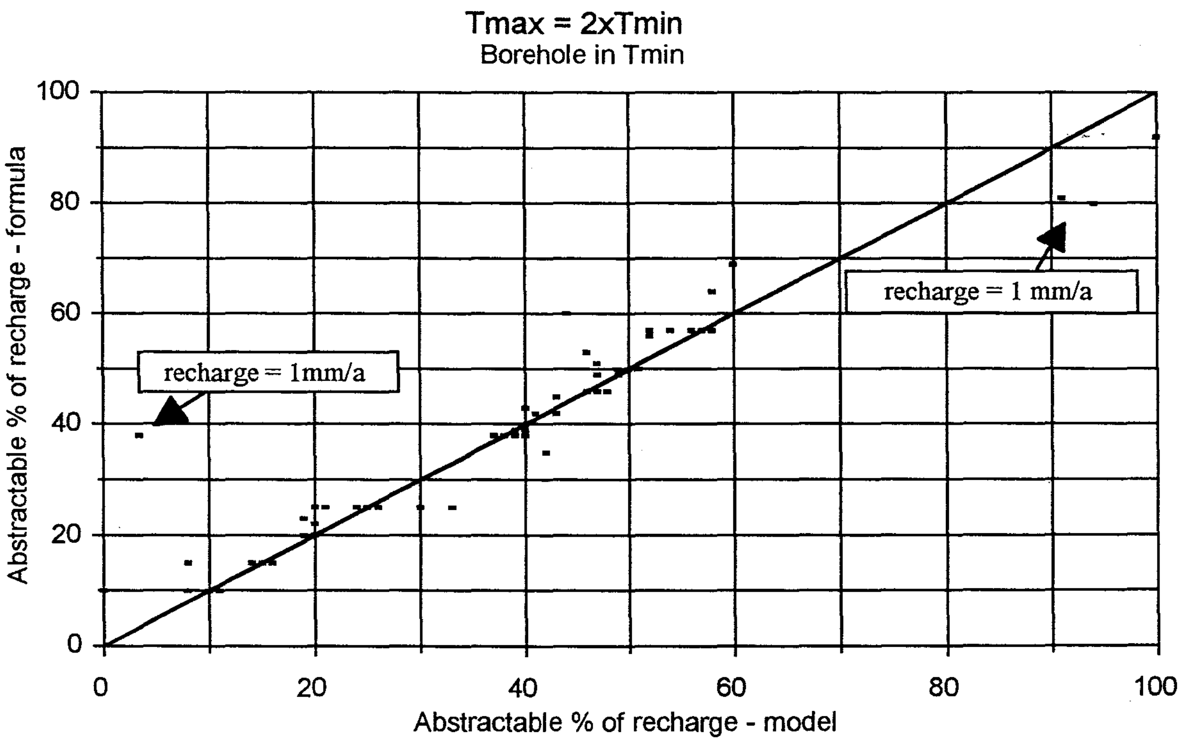
Borehole	Production yield (m^3/day)	Equation 3.1 yield (m^3/day)
BRG 7	5 - 6	11
DEW 1A	35	50
RV 205	30	27

Figure 3.7 A comparison between abstractable proportion of recharge values obtained from the model and values obtained using equation 3.1






Tmax = 13.3xTmin; 20xTmin; 40xTmin
Borehole in Tmax
Abstractable % of recharge - formula
Abstractable % of recharge - model
100
90
80
70
60
50
40
30
30
40
50
60
70
80
90
100
recharge = 1 mm/a or 5 mm/a for all points below the dotted line


Tmax = 2xTmin
Borehole in Tmin
Abstractable % of recharge - formula
Abstractable % of recharge - model
100
80
60
40
20
0
0
20
40
60
80
100
recharge = 1mm/a
recharge = 1 mm/a

3.4 A GUIDELINE FOR ESTIMATING ANISOTROPY

Table 3.2 can be used as a guideline for estimating anisotropy values.

Table 3.2 Guidelines for estimating anisotropy values

VALUE	DESCRIPTION	EXAMPLES
0.1	A highly linear flow system where transmissivity along the length of the aquifer (x-axis) is ten times the transmissivity along the aquifer's y-axis.	Aquifers characterised by a parallel fracture pattern, for example those associated with dolerite dyke intrusions, faults and fold hinges.
0.5	Transmissivities along the x-axis are twice those along the y-axis. This represents a system where there is a preferred fractured orientation in an environment with a strong secondary fracture orientation.	Weathered and fractured rock aquifers with a preferred fracture orientation, for example certain granitic and basaltic aquifers.
1.0	Isotropic aquifer. This represents an equal fracture pattern in the x and y directions and is equivalent to a porous medium.	Primary aquifers. Homogeneous, weathered rock aquifers. Fractured rock aquifers that display a perpendicular grid fracture pattern of equal intensity.

3.5 A GUIDELINE FOR ESTABLISHING SEEPAGE FACE WIDTH AND RECHARGE AREA

The aquifer's outflow width and the recharge area can be estimated by combining the geological and topographical setting of the aquifer. Vegter (1995) notes that the water table is a subdued replica of the topography over most of the country. For this reason it can be assumed that groundwater flow is perpendicular to the topographic contours, unless information to the contrary is available. It follows that in many instances the width of the seepage face can be determined by topography, or the width of the valley bottom. In the case of single borehole analyses the seepage face should be taken perpendicular to the groundwater flow at the borehole site. In determining the width of the seepage face, the hydrogeologist may also need to identify the aquifer's boundaries on either side of the borehole. This can be problematic, however, there are certain geological and topographical features that can be of assistance. For example, thick coarse grained, unfractured dolerite dykes or granitic ridges are likely to act as groundwater boundaries.

In determining the recharge area of an aquifer, Bredenkamp, et al. (1995) suggest that it can be delineated as the area bounded between dolerite dykes, by piezometric flow lines or a topographic divide. In many instances, for example where the geology complex, it may not be possible to determine the recharge area, and therefore it would not be possible to use the method described in this chapter.

The method was developed using small catchment areas (1 km^2 and 5 km^2), because it is in small catchments that recharge could be the limiting factor that determines the sustainable groundwater resource. The method should be used with reservations when the borehole is located at the base of a large catchment because of the problem with determining the contributing recharge area, and because recharge is unlikely to be limiting when a large catchment area is available. Likewise, it is not easy to estimate the recharge area in cases where very deep water strikes are encountered. These problems were experienced during the verification of this method (Chapter 7). As a result only three out of the fifteen monitored boreholes used in the verification study could be used to assess the recharge based method outlined in this chapter.

One of the motivations for undertaking this study is because many rural villages are dependant on single boreholes for their domestic requirements. Most of these villages are located in the Karoo Sequence. The average water strike depth in Karoo aquifers is in the region of 30m - 50m (Vegter, 1995) which, in many cases would make it possible to estimate a recharge area. An example of suitable areas for the application of the recharge method may be found in the hilly areas of the Eastern Cape and KwaZulu-Natal where many boreholes are located in Karoo aquifers and in relatively small catchments. Unfortunately very few monitored boreholes could be found in these areas.

3.6 A GUIDELINE FOR ESTABLISHING TRANSMISSIVITY VALUES

Transmissivity values should be obtained using the appropriate analytical methods applied to constant discharge and recovery test pump curves (Kruseman and De Ridder, 1991). Alternatively, transmissivity can be estimated from a pumping borehole, according to Kirchner and Van Tonder (1995) by:

$$T = 10 \,.\, Q \qquad \text{eq.3.2}$$

where:

T = transmissivity in m^2/d

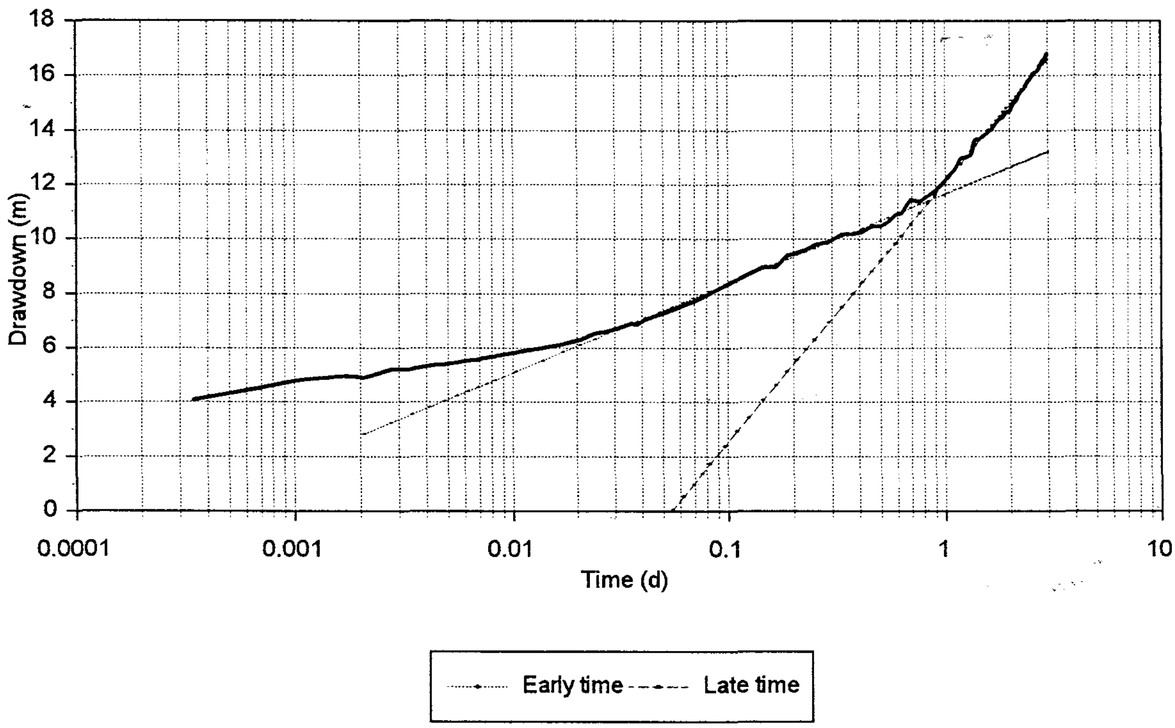
Q = borehole yield in l/s. (Kirchner and Van Tonder (1995) did not define "borehole yield". It is assumed to refers to the borehole's pumping rate rather than its blow yield).

Where the borehole is located in the higher transmissivity zone, the lower transmissivity value (Tmin) could be estimated by using average regional transmissivity values, or the lower transmissivity values obtained in the hydrogeological environment in which the borehole is located. In the case of double porosity aquifers, Tmin may be obtained by calculating transmissivity using the Cooper-Jacob straight-line method applied to the late-time drawdown segment of the constant discharge test curve (Figure 3.8).

The double-porosity theory regards a fractured rock formation as consisting of two media: the fractures and the matrix blocks (Kruseman and De Ridder, 1991). The aquifer thus consists of two coexisting hierarchies of porosity and conductivity: primary porosity and low permeability in the aquifer matrix, and low storage capacity and high permeability in the fractures. The late-time pumping test data may reflect the rate of drawdown related to the matrix permeability, hence its transmissivity may be obtained using the Cooper-Jacob method, so long as the late-time drawdown is controlled by double-porosity and not boundary conditions (Kirchner and Van Tonder, 1995).

While conceptually, the double-porosity model differs from the modelled aquifers used in developing the abstractable proportion of recharge (as presented in this chapter), for all intents and purposes, a transmissivity value obtained from the late-time segment of the drawdown curve is likely to be a fair estimate of Tmin.

Figure 3.8 Early- and late-time slopes from a constant discharge test



3.7 CONCLUSIONS

The method described in this chapter can be used to obtain an estimate of a borehole's yield based on recharge to the aquifer in which the borehole is located. The method is based on certain assumptions which will limit its applicability. These assumptions are summarised below.

Recharge area
The area over which the aquifer is likely to receive recharge needs to be established. This limits the method to areas which are not characterised by complex geology, where the borehole is located within relatively small catchments (less than approximately 10 km^2) and where the water strikes in the borehole are shallow (less than approximately 50 m).

Recharge value
An acceptable mean recharge value needs to be established.

Seepage face
The width of the aquifer's outlet at the borehole or slightly down gradient needs to be estimated. This limits the method to those cases where such an estimate can be made due to the geological or topographical environment. The calculation of the abstractable proportion of recharge is very sensitive

to this variable when the seepage face is less than 1000 m.

Transmissivity

The aquifer needs to consist of a narrow linear zone of a relatively high transmissivity, adjacent to which lie zones of lower transmissivity, and these transmissivity values need to be established. Whilst the transmissivity of the zone in which the borehole is located can be obtained from test pumping the borehole, the transmissivity of the other zone would usually need to be estimated.

Anisotropy

An estimate of the degree of preferential flow in the x -y plane, where x is the down gradient direction needs to be made.

4. GROUNDWATER RESOURCE EVALUATION BASED ON STORAGE

4.1 INTRODUCTION

In order to establish the sustainable exploitation potential of a groundwater resource, it may be necessary to establish how much water is held in storage and what percentage can or should be removed in order for the resource to last through years of less than average rainfall. It would be particularly important to assess this parameter in aquifers which receive infrequent recharge and which have limited storage potential. A thin, hard rock aquifer with limited porosity in the Kalahari Basin would be a good example of such a case.

The method requires the calculation of the theoretical abstractable volume of water stored in the aquifer (S_t), where:

$$S_t = A \,.\, b \,.\, S \qquad \text{eq.4.1}$$

where:

A = area of the aquifer
b = mean aquifer thickness
S = storativity

and the proportion of that (E_s) which is practically and sustainably abstractable:

$$E_s = (S_t \,.\, D) / N \qquad \text{eq.4.2}$$

where:

D = abstractable proportion of groundwater
N = number of years with no recharge

Each of these variables, will be discussed separately. The D-value is obtained from equation 3.1, as this represents the abstractable proportion of groundwater within the capture zone of the borehole.

Equation 4.1 assumes that the available resource can be abstracted if a sufficient number of suitably spaced boreholes exist, whereas equation 4.2 takes the borehole locations and the recharge cycles into account.

4.2 AREA

The size of an aquifer is difficult to determine without detailed geological mapping and an inventory of existing boreholes and their geological logs. In the case of small scale domestic rural water supplies neither of these are usually available due to budget constraints and a lack of boreholes that may penetrate the aquifer under investigation. Under such circumstances the area could be estimated from geological and topographical maps, and aerial photographs. The hydrogeologist would need to assess the error margin that such an approach would give, and reject the storage calculation if this was significant. The aquifer's area should not be confused with the recharge area - the former being significantly smaller and not including the high lying areas which can be important recharge zones, but have little storage potential.

In order to reduce the surface area to a more realistic value representative of the saturated rock volume, it is proposed that the area be multiplied by the drilling success rate in the region, or the drilling success rate in an area of similar hydrogeology. If 30% of the boreholes in the region did not yield any water, it would be better to assume that the aquifer covers 70% of the area mapped from the remote sensing study, rather than the full area. If drilling success rates cannot be obtained from DWAF's national groundwater data base, then the Borehole Prospects map in the map series entitled "Groundwater Resources of South Africa" (Vegter, 1995) should be consulted.

Taking borehole success rate into account, equation 4.1 can be modified to:

$$S_t = A \cdot b \cdot S \cdot w \qquad \text{eq.4.3}$$

where:

w = fraction of successful boreholes

While Vegter (1995) describes a successful borehole as one which yields at least 0.1 l/s, boreholes which penetrate saturated rocks with low permeabilities could yield less than 0.1 l/s. For this reason it would be preferable to use all water yielding boreholes when determining the 'w' value. Because it is difficult to determine the saturated area of an aquifer, the storage based method is subject to large errors.

4.3 AQUIFER THICKNESS

Like the aquifer's area, it is difficult to determine the aquifer's thickness without a detailed hydrogeological study of the area. Of importance is the mean thickness of that part of the saturated zone which contains most of the available groundwater. Methods which have been used to determine this thickness, and which are based on drilling records and borehole logs are discussed below.

A study of DWAF's groundwater data base revealed that most of South Africa's accessible groundwater is stored in the upper fractured and weathered zone of hard-rock formations, except in the folded quartzitic sandstones of the Table Mountain Group (Vegter, 1995). The saturated thickness of this zone was seldom found to exceed a mean of 25 m. Although the thickness of this zone for a specific area can be obtained from local geological logs, it may be unreasonable to assume that the values obtained are representative of the entire aquifer.

In a study of Karoo aquifers in the Upper Kei Basin of the Eastern Cape Province, DWAF (1993) used the distance between the piezometric surface and the main water strike in 466 boreholes to establish a regional aquifer thickness. Here it was found that 50% of the water interceptions are within 20 m of the piezometric surface, and that there is a sharp decline in the number of interceptions below this level. The regional aquifer thickness was taken as 20 m. The assumption this method makes is that the entire rock mass between the piezometric surface and the main water strike is saturated. This may be an acceptable assumption in certain primary aquifers, or in secondary aquifers where the main water strikes are located within the weathered zone. However, in cases where the aquifer is confined or where the main water strikes are located below the saturated weathered zone, this method is likely to over-estimate the aquifer's thickness.

The distance between the first water strike or the depth at which moisture was first encountered in the borehole, and the last water strike, may be another way in which the aquifer's thickness could be determined. Where the deepest water strike is well below the saturated weathered zone, this method would also over-estimate the aquifer's thickness.

As a rough regional guideline Vegter (1995) states that the mean thickness of the aquifer can be taken as half the optimal drilling depth below the water level. These depths can be obtained from the Groundwater Resources of South Africa maps (Vegter, 1995). Although regional aquifer thicknesses should be taken into account, emphasis should be placed on site specific thicknesses from geological logs and a conceptual model of the aquifer. This model should account for variations in the saturated thickness over the aquifer's area, and the possible pinching out of the aquifer at its edges. Because a mean aquifer thickness is difficult to establish, the storage based method is subject to large errors.

4.4 STORATIVITY

The coefficient of storage or storativity of an aquifer, relates to that portion of water held in storage which can be released in response to pumping (a definition is provided in Chapter 1). Storativity values (S) are most easily derived from test pumping a borehole and monitoring the drawdown in observation boreholes, and then applying the appropriate hydraulic equation to solve for S. The appropriate equation for various hydraulic scenarios can be found in Kruseman and De Ridder (1991).

Bredenkamp, et al. (1995) caution against obtaining an S-value from a single observation borehole in secondary aquifers, as this value appears to decrease with distance from the pumped borehole, and at large distances the S-value may become unrealistically small. They state that S-values obtained from pumping tests in a fractured rock system can be unreliable, a problem compounded by the fact that fractured rock aquifers cover most of the country.

The reason for the changing S-value with distance from the pumped borehole in fractured rock aquifers, may be related to the pressure relationship between the matrix or relatively small fractures, and the larger fractures. Consider an aquifer which consists of numerous small fractures or a matrix with low permeability and a high storage capacity on the one hand, and a few, large permeable fractures with low storage capacity on the other hand. "Close to the pumping well, pressure in the large fractures declines rapidly relative to its rate of decline in the small fractures. The latter therefore release a relatively large amount of water into the large conductive fractures due to sizeable local pressure gradient between the small and large fractures reservoirs. Hence S is large. Far from the pumping well, the pressure gradient between the small and large fractures is relatively small. Therefore, water release from the small to the large fractures occurs very slowly. Most of the initial drawdown at a great distance is associated with water release from storage in the large fractures. Hence S is small." (Kirchner and Van Tonder, 1995, p190).

Methods for determining the S-value which are not based on pumping tests are discussed in Bredenkamp, et al. (1995). Unless an acceptable S-value can be obtained, the storage based method for quantifying a groundwater resource should not be used.

4.5 NUMBER OF YEARS WITH NO RECHARGE

Storage needs to be sufficient to bridge cycles of no recharge. In a regional study in the Eastern Cape, DWAF made a conservative assumption that no recharge takes place during years of below average rainfall (DWAF, 1993). The number of years with no recharge was taken as the longest span of below average rainfall years on record. It is unlikely that no water enters the aquifers during these periods, and therefore such a figure may be too conservative. As an alternative, it is proposed that the number of years without recharge be taken as the longest span of years during which annual rainfall is below one standard deviation below the mean rainfall. Precipitation data for tertiary catchments from Surface Water Resources of South Africa 1990 (Midgely et al., 1994) can be used if no local rainfall records are available.

4.6 CONCLUSIONS

The applicability of this method is limited because of the difficulty in quantifying the necessary parameters on which the method is based. The surface area of an aquifer is generally difficult to define, and an aquifer's saturated thickness varies over its area. Because S-values can vary significantly within an aquifer (see Appendix 3), and because of the problems associated with establishing representative S-values, large errors can be made in determining the volume of water that an aquifer can release from storage.

The storage based method for quantifying a groundwater resource is subject to large errors and consequently has very limited value for rural water supplies. It is sensitive to each parameter used in the method, and they are all difficult to quantify. If this method is to be used with an acceptable degree of accuracy, the volume of saturated rock, a suitable storativity value and the number of years without recharge would need to be established.

5. GROUNDWATER RESOURCE EVALUATION BASED ON THROUGHFLOW

5.1 INTRODUCTION

An indication of an aquifer's exploitation potential can be obtained by assessing the rate at which water flows through it under steady state. The following equations based on Darcy's Law are used in order to establish the aquifer's throughflow:

$$Q = K \,.\, I \,.\, A \qquad \text{for unconfined aquifers} \qquad \text{eq.5.1}$$

where:

Q = discharge in m^3/day
K = hydraulic conductivity in m/day
I = hydraulic gradient
A = cross sectional area of the aquifer

$$Q = T \,.\, I \,.\, w \qquad \text{for confined aquifers} \qquad \text{eq.5.2}$$

where:

T = transmissivity
w = width of the aquifer

If the abstractable proportion of groundwater (as determined in Chapter 3) is taken into account in order to give a better indication of a single borehole's yield potential, then equations 5.1 and 5.2 could be written as:

$$Q = K \,.\, I \,.\, A \,.\, D \qquad \text{for unconfined aquifers} \qquad \text{eq. 5.3}$$

$$Q = T \,.\, I \,.\, w \,.\, D \qquad \text{for confined aquifers} \qquad \text{eq. 5.4}$$

where:

D = the abstractable proportion of groundwater

5.2 CALCULATION OF THROUGHFLOW

Hydraulic conductivity
Hydraulic conductivity (defined in Chapter 1) indicates the ability of a water-bearing formation to transmit water, and is dependant on the size and number of pores in the aquifer material. In fractured rock aquifers the density, apertures and roughness of the fractures would effect the K-value.

Hydraulic conductivity can be determined in many ways. A relatively accurate and easy way is through pump testing, which involves the monitoring of water levels in observation wells near the pumping well. The advantage this method has over other methods, is that it gives an integrated hydraulic conductivity over a sizeable aquifer section. Other methods are based on flow measurements in a laboratory, tracer tests, slug tests and empirical equations based on porosity, grain diameter and shape factor.

Laboratory analysis requires measuring flow through a column of aquifer material under constant or falling head conditions with a permeameter, and applying Darcy's Law. Obtaining an undisturbed sample which is not effected by the way it is packed into the permeameter can be a problem.

Hydraulic conductivity can also be obtained by measuring the time taken for a tracer to travel between two boreholes. The boreholes need to be in close proximity due to slow groundwater travel times, and the flow direction has to be known. If the aquifer is stratified or fractured, the K-value obtained may be much higher than the average, due to preferential flow paths along the transmissive sections of the aquifer. The decay in concentration of a tracer in a single hole can also be used to determine hydraulic conductivity. Since the value obtained would be related to the hydraulic conditions around the borehole, this value would not necessarily be representative of the entire aquifer. This problem also applies to slug tests, where the change in piezometric surface after the rapid removal of a volume of water or a 'slug' is monitored.

Hydraulic gradient

If more than one borehole is present, the hydraulic gradient can be determined by measuring their rest water levels and the distance between them. Because the water table is generally believed to be a subdued replica of topography over the greater part of the country (Vegter, 1995), an estimate of the maximum hydraulic gradient can be obtained by taking the channel slope along the envisaged groundwater flow path.

The aquifer's width, cross sectional area and transmissivity

An aquifer's cross sectional area (width multiplied by thickness) is required in order to determine throughflow in unconfined aquifers. The thickness of the aquifer may be very difficult to determine. This issue was discussed in the previous chapter (section 4.3), while the determination of the width or seepage face of the aquifer was discussed in Chapter 3 (section 3.5).

A transmissivity value is needed for confined aquifers. This can be obtained from test pumping the borehole or boreholes which penetrate the aquifer. The transmissivity value should ideally take into account the changes in transmissivity over the width of the seepage face. Because this is difficult to determine, the following options should be considered:

- Using the width and transmissivity of the narrow high transmissivity zone - the Tmax zone described in Chapter 3. Although the width of this zone may be difficult to determine, if it is sufficiently wide and transmissive, most of the groundwater could flow through this section of the aquifer.
- Using the width and transmissivity of the broad low transmissivity zone. If the Tmax zone of the aquifer is narrow and not significantly more permeable than the aquifer as a whole, the matrix transmissivity or T-min as described in Chapter 3, used with the full width of the seepage face is likely to give a more realistic throughflow value than if the Tmax zone alone was used.

5.3 CONCLUSIONS

Large errors can be expected using this method if the aquifer's parameters are incorrectly established. This is because the calculation of throughflow is sensitive to errors in all the parameters on which this method is based. Furthermore, equations 5.1 and 5.2 will not necessarily reflect hydraulic conditions in secondary aquifers. The method is based on Darcy's Law, which is applicable to laminar flow in porous media. Although groundwater movement is generally slow, and therefore laminar as opposed to turbulent flow can be assumed in most environments, this may not be the case where large secondary openings exist, or where hydraulic gradients are steep (Todd, 1980).

Unless more than one borehole exists, the hydraulic gradient needs to be estimated using topographical maps. Although the water table or piezometric level may mirror topography in many parts of South Africa, the determination of hydraulic gradient using channel slopes, especially in areas with steep valley floors, will likely lead to significant errors. Because it is difficult to establish average hydraulic parameters which represent variations across the aquifer's seepage face, the method is subject to large errors and is of limited value to rural water supply studies.

6. BOREHOLE YIELD ASSESSMENT METHODS BASED ON TEST PUMP DATA

6.1 INTRODUCTION

Previous chapters have looked at methods of determining aquifer yields and a method of estimating the proportion of the aquifer yield abstractable from a single borehole. The final borehole yield recommendation will depend on interpretation of the test pump data. Presented in this chapter is a review of established methods and newly developed methods for recommending borehole abstraction rates based on test pump data. The following chapter compares these methods and the methods based on an aquifer yield assessment to established yields from production boreholes.

Several experienced hydrogeologists were asked how they arrive at their recommended borehole yields. In most cases the answers were vague, with several references to "experience" and to the recovery test which follows the constant discharge test. These tests are described in section 6.2. In general, hydrogeologists tend to combine borehole and aquifer yield analyses. These include an assessment of test pump data, geological data, the topographic position of the borehole and climatic data. The type of test pump programmes carried out usually include the multiple discharge test (step test), a constant discharge test and a recovery test. The geological data usually includes the type and extent of rock formations present and the degree of weathering and fracturing. The climatic data which is used to obtain an indication of aquifer recharge, usually includes an estimate of the mean annual precipitation and the occurrence of droughts in the area.

Hydrogeologists differ in the degree of quantitative and qualitative analyses they use prior to recommending a borehole's yield. Some hydrogeologists place their emphasis on a qualitative assessment of the shape of test pump curves, while others will tend to combine qualitative test pump curve assessments with quantified borehole and aquifer parameter analyses. While the qualitative information may give an indication of the type of aquifer, and the presence and nature of hydraulic boundaries, quantitative information may include an assessment of the aquifer's transmissivity, storativity and recharge, as well as an assessment of how the borehole responds to pumping.

This study recognises the importance of establishing the hydraulic properties of an aquifer and the need to understand the geological environment in which the borehole is located. Hydraulic and geological conditions such as: transmissivity; storativity; the nature of boundaries (for example recharge, low permeability or barrier boundaries); whether the aquifer is characterised by double porosity, leaky conditions or vertical fractures, etc., all affect groundwater flow towards a pumping borehole and thus its sustainable yield. While an initial assessment of the geological environment is usually obtained from air photographs, satellite photographs, geological maps, topographical maps, geophysical surveys and drilling logs, a more comprehensive understanding of the geological environment is obtained by combining this information with test pump data. Hydrogeologic conditions affecting test pump curves are discussed in the following section, after a brief overview of borehole pumping tests. Section 6.2 also discusses the numerical interpretation of test pump data and justifies the use of the Cooper-Jacob approximation of the Theis equation. Section 6.3 presents methods to estimate the sustainable yield of a borehole based on the analysis of test pump data.

6.2 THE INTERPRETATION OF TEST PUMP DATA

6.2.1 Recommended test pump procedures

The type of test pump programmes carried out on the borehole generally depends on the planned water usage (Weaver, 1993), but often includes a multiple discharge test (step test), a constant discharge test and a recovery test.

Multiple discharge test
The multiple discharge test or step test is used to determine the hydraulic efficiency of the borehole at different pumping rates and to recommend a suitable pumping rate for the constant discharge test. The test involves monitoring the drawdown in the borehole while the discharge is increased in steps. Each step is usually carried out for no less than sixty minutes. A comprehensive description of the methods used to analyse the data obtained from multiple discharge tests is given in Kruseman and De Ridder (1991). The multiple discharge test can also be used to establish the depths of the water strikes and the thickness of the weathered formation, so long as the initial steps are carried out for a sufficient duration at relatively low discharge rates (Woodford, pers comm.). Information on the depth of the water strikes and the thickness of the weathered zone can be vital in the determination of daily abstraction rates. The relevance of this is discussed in section 6.3.

Constant discharge test
The constant discharge test is used to determine aquifer's hydraulic parameters like transmissivity, storativity (if an observation well exists) and a conceptual model of the aquifer's hydraulic scenario, for example the presence of impermeable or recharge boundaries. The test involves monitoring the drawdown in the borehole while the discharge is kept constant. A description of the various methods used to analyse the data obtained from constant discharge tests is given in Kruseman and De Ridder (1991). The duration of the constant rate test may be determined by the information and level of reliability required (Weaver, 1993). It is common practice to run the test for about eight hours for boreholes to be equipped with hand, solar or wind driven pumps, and for forty eight hours for boreholes to be equipped with electricity or diesel driven pumps which are to be operated on a daily basis.

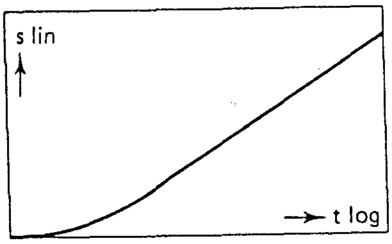
Recovery test
The recovery test can be used to calculate aquifer's hydraulic parameters, to establish whether recharge has taken place during or shortly after the constant discharge test and whether the storativity values vary throughout the aquifer (Driscoll, 1986). It can also give an indication of the extent of the aquifer, or the extent and connectiveness of fractures. The Geological Society of South Africa recommends this test be continued until: the water level in the borehole recovers to its pre-pumping level; the water level recovers to less than 5% of the total drawdown experienced during the constant rate test; three readings in succession are identical; or the test is carried out for half the length of time of the constant discharge test (Weaver, 1993). In order to establish whether the aquifer has been significantly dewatered during the constant discharge test, and in order to accurately apply the recovery test data for estimating sustainable borehole yields (described in section 6.3), it may be preferable to monitor recovery water levels for at least the same duration as the constant discharge test.

6.2.2 Hydrogeologic conditions affecting test pump curves

A conceptual model of the aquifer can be developed from hydrogeological mapping, borehole logs and the shape of the test pump curves. This section presents typical drawdown curves obtained from pumping tests under different hydrogeological conditions. It also describes which portion of the curves to interpret in order to obtain a transmissivity value to be used in quantifying the sustainable yield of a borehole. The figures have been copied from Kruseman and De Ridder (1991).

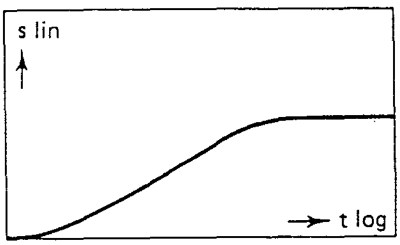
Figure 6.1 shows a typical drawdown curve for confined aquifers which meets the assumptions of the Theis equation for radial flow in porous media (section 6.2.3). The semi-log plot shows that the log (time)-drawdown relationship is initially not log-linear due to casing storage, but at later times it is. The portion of the slope which is affected by casing storage should not be used to determine aquifer transmissivity. A similar curve could be obtained from an aquifer with a single plane vertical-fracture in a low permeability matrix (Kruseman and De Ridder, 1991). The straight line portion of the curve, which reflects flow from the matrix to the fracture would be used to obtain the aquifer's transmissivity.

Figure 6.1 Theoretical drawdown curve for a confined aquifer



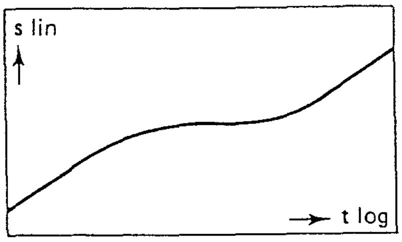
In the case of leaky aquifers (Figure 6.2), the early-time curve is similar to the early-time curve in Figure 6.1. At medium pumping times, more and more water from the aquitard (a saturated, but poorly permeable stratum) is reaching the aquifer. The drawdown curve eventually flattens when leakage equals the pumping rate, and steady state conditions are achieved. In the case of a recharge boundary, for example a dam or a river, the late-time portion of the curve will not become horizontal if the recharge rate is less than the pumping rate. In both leaky aquifers and where recharge boundaries exist, the straight line portion of the curve prior to the late-time horizontal section should be used to establish the transmissivity of the aquifer.

Figure 6.2 Theoretical drawdown curve for a leaky aquifer or a recharge boundary



In an unconfined aquifer exhibiting delayed yield (Figure 6.3), the semi-log plot shows two parallel straight line segments at early and late pumping times, with a flat segment in between. The flat, 'delayed yield' portion of the drawdown curve is caused by gravity drainage replenishment from the pore space above the cone of depression. The reason a double porosity fractured rock aquifer displays a similar drawdown curve is discussed in section 6.2.3 (under the heading "Justification for use of the Cooper-Jacob approximation of the Theis equation for interpreting test pump data"). Because the horizontal portion of the drawdown curve reflects gravity drainage or leakage from the aquifer's matrix blocks, it should not be used to determine the aquifer's transmissivity.

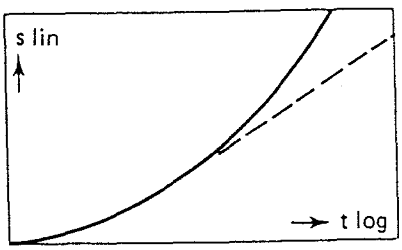
Figure 6.3 Theoretical drawdown curve for an unconfined aquifer with delayed yield, or a double porosity fractured aquifer



When the cone of depression reaches a barrier boundary on one side of a pumped well, it can not expand any further in that direction (Figure 6.4). The cone of depression must deepen more rapidly in all other directions to maintain the yield to the well, thereby steepening the drawdown curve. If the aquifer is of limited lateral extent, the drawdown curve will increase exponentially as the aquifer is dewatered. The slope prior to boundary effects (the dashed line in Figure 6.4) would reflect the aquifer's transmissivity.

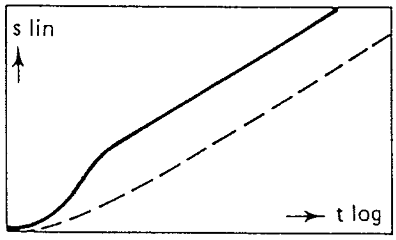
A similar curve to that found in single boundary conditions can be obtained if fractures are dewatered in a fractured rock system, for example in a fractured dyke aquifer. In this case, the early-time portion of the drawdown slope (the dashed line in Figure 6.4) would reflect flow from the permeable fractures towards the borehole, and the late-time portion of the slope would reflect flow from the less permeable matrix to the fractures. Whether to obtain the transmissivity value from the early- or late-time portion of the drawdown curve, depends on which borehole yield assessment method is used. Section 6.3 presents two borehole yield assessment methods which apply the early-time transmissivity value (the drawdown-to-boundary and distance-to-boundary methods), and one method which makes use of the late-time transmissivity value (the late-T method). The use of early- and late-time transmissivity values are explained in the description of these methods.

Figure 6.4 Theoretical drawdown curve for a barrier boundary or some fractures dewatered (The dashed line reflects the pre-boundary drawdown slope)



With a partially penetrating borehole (Figure 6.5), vertical flow conditions are induced in the aquifer. These are accompanied by extra head losses in and near the borehole. The straight line portion of the curve should be used to establish the aquifre's transmissivity.

Figure 6.5 **Theoretical drawdown curve for a borehole which partially penetrates the aquifer** (The dashed line represents the theoretical curve if the borehole fully penetrated the aquifer.)



A note on casing storage
If the first ten minutes or so of the time-drawdown curve is steep in relation to the rest of the curve, it may be due to casing storage. This can be checked by calculating the volume of water held in the borehole and comparing that to the discharge rate. Obviously any curve generated by casing storage should be ignored in the analysis of aquifer parameters.

6.2.3 Numerical interpretation of test pump data

The Cooper-Jacob approximation of the Theis equation

The borehole yield assessment methods presented in section 6.3 which require the interpretation of constant discharge test data, are based on the Theis (1935) transient state radial flow equation:

$$s = Q\,W(u) / 4\,\pi\,T \qquad \text{eq.6.1}$$

where:

u	$= r^2 S / 4 T t$
s	= drawdown measured at a distance r from the pumped well
Q	= discharge
S	= storativity
T	= transmissivity
t	= time since pumping started

W(u) is read as the well-function of u or the Theis well function and is an exponential integral which varies with u. Values for W(u) as a function of u are available in standard texts (for example, Driscoll, 1986 and Todd, 1980) In order to use the Theis equation to calculate aquifer hydraulic parameters from test pump data, curve matching is required where a "type curve" of W(u) is plotted against 1/u on logarithmic paper. On another sheet of the same scale, drawdown is plotted against t/r^2. The two plots are then overlain so that the position of best match is located. An arbitrary match point is then selected, and the coordinates of this match point are recorded. With values of W(u), u, s and r^2/t thus determined, S and T can be obtained from the following equations:

$$T = (Q / 4 \pi s) W(u) \qquad \text{eq.6.2}$$
$$S = 4 T (t / r^2) u \qquad \text{eq.6.3}$$

The Theis solution is based on the following assumptions and conditions, (Kruseman and De Ridder, 1991):

- the aquifer is confined;
- the aquifer has a seemingly infinite areal extent;
- the aquifer is isotropic, homogeneous and of uniform thickness over the area affected by pumping;
- prior to pumping the piezometric surface is horizontal (or nearly so) over the area affected by pumping;
- the aquifer is pumped at a constant discharge;
- the pumped well penetrates the entire aquifer and thus receives water by horizontal flow;
- water removed from storage is discharged instantaneously with the decline of head;
- the diameter of the well is small, i.e. the storage in the well can be neglected.

These ideal conditions are extremely rare, if not absent in most South African aquifers. South African aquifers are seldom infinite in extent, isotropic, homogeneous or of uniform thickness due to the heterogeneities related to fracturing, but are commonly confined or semi-confined and usually have 'nearly' horizontal piezometric surfaces. In spite of the limitations imposed by the Theis assumptions, acceptable transmissivity values can be obtained in many South African aquifers using groundwater flow equations that are based on the Theis equation (Phillips, 1994). This point is discussed later under the heading: "Justification for use of the Cooper-Jacob approximation of the Theis equation for interpreting test pump data".

The Cooper-Jacob approximation of the Theis equation (Cooper and Jacob, 1946) avoids the labourious curve fitting procedures, but is applicable only when the value for u is small ($u < 0.01$).

Equation 6.3 can be written as:

$$u = r^2 S / 4 T t \qquad \text{eq.6.4}$$

Here it is apparent that u will decrease as r decreases and t increases. The Theis equation (eq.6.1) can be rewritten as:

$$s = (2.3 Q / 4 \pi T) \log(2.25 T t / r^2 S) \qquad \text{eq.6.5}$$

In confined systems meeting the Theis assumptions, a plot of s vs. log t forms a straight line, which can be extended until it intersects the time axis where $s = 0$ and $t = t_0$, with the slope of the line being related to T by:

$$T = 2.3 Q / 4 \pi \Delta s \qquad \text{eq.6.6}$$

where Δs is the drawdown per log cycle of t, and

$$S = 2.25\ T\ t_0\ /\ r^2 \qquad \text{eq.6.7}$$

To check for the validity of this method ($u < 0.01$) the values are substituted into equation 6.4 and a minimum pumping time, t is calculated. A pump test must be of longer duration than this calculated time if the Cooper-Jacob method is to be applicable.

Justification for use of the Cooper-Jacob approximation of the Theis equation for interpreting test pump data

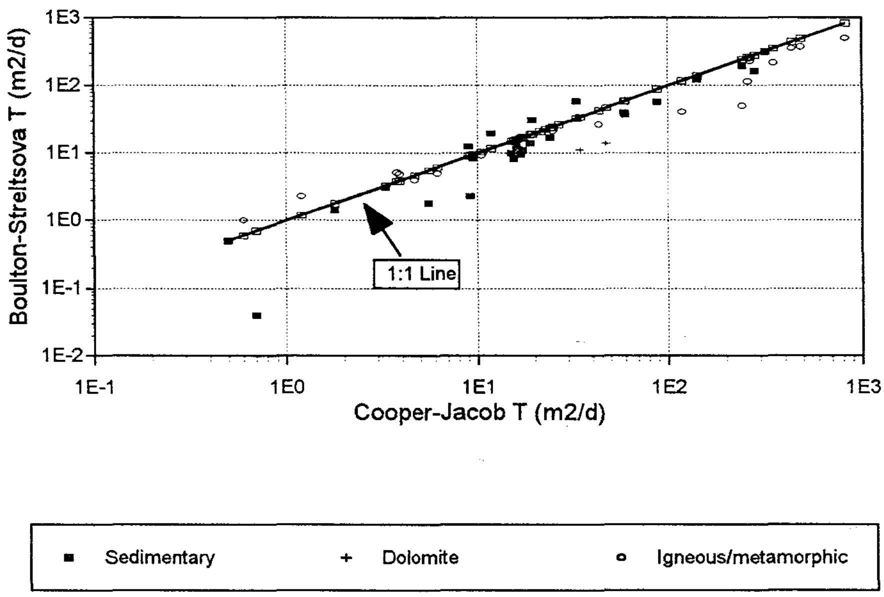
There is an on-going debate about the nature of groundwater flow in fractured media and its response to pumping. Many theoretical models have been developed to describe aquifer response to constant discharge pumping, all of which assume simplified regular fracture systems, and all of which are complex due to the complex mechanism of fluid flow in fractured rocks. Some of these methods are described by Kazemi et al. (1969), Warren-Root (1963), Gringarten-Witherspoon (1972) and Boonstra-Boehmer (1986), and most are applicable to observation wells rather than to pumped wells. A drawback with many of the fractured rock test pump analysis methods is that they may require labourious curve fitting, like the Boonstra-Boehmer method for flow in single vertical dykes and the Gringarten-Witherspoon method for flow through single vertical fractures.

Many fractured aquifers can be described by the double porosity aquifer concept. This theory regards a fractured rock formation as consisting of interconnected fractures of high permeability and low storage, which serve as conduits for flow, and matrix blocks of higher storativity and lower permeability. The effect of water abstraction from these aquifers exhibits a strong time dependancy. During the early-time response flow to the borehole comes from storage in the highly permeable fractures. The resulting drop in the piezometric head of these fractures creates a pressure gradient which induces leakage from the surrounding blocks, leading to a temporary stabilizing of the drawdown curve. With continued pumping, the pressure gradient between the matrix and the fractures decreases and leakage occurs more slowly, causing the rate of drawdown, and thus the slope of the drawdown curve, to increase.

The flow towards the well in double porosity systems is considered to be through the fractures, radial and in transient state. Transient or unsteady flow conditions imply a state of non-equilibrium, where flow rates and hydraulic gradients are changing over time and direction. While some of the double porosity models assume the flow from the matrix to the fractures is in pseudo-steady state, Boulton and Streltsova (1977) developed a transient matrix-to-fracture flow solution because the pseudo-steady-state interporosity flow models do not have a firm theoretical justification (Kruseman and De Ridder, 1991).

The borehole yield assessment methods which are described later in this chapter, and which require the interpretation of constant discharge test data, however, are all based on the Cooper-Jacob approximation of the Theis transient state flow equation (described in the following section). The Cooper-Jacob analysis has the advantage of being easy to apply in comparison to the methods which were developed to describe aquifer response to pumping in fractured media. Although not conceptually correct in many fractured rock environments, Phillips (1994) showed that the Cooper-Jacob analysis can provide acceptable estimates of transmissivity in a wide range of geological environments. Phillips (1994) compared transmissivity values obtained using the Cooper-Jacob analysis which assumes radial groundwater flow in an isotropic, homogeneous aquifer, to the Boulton-Streltsova (1977) analysis which was developed for groundwater flow in fractured, double porosity aquifers. Figure 6.6 shows the similarity of the transmissivity values obtained using these two analytical methods.

Figure 6.6 A comparison between transmissivity values obtained using the Cooper-Jacob and the Boulton-Streltsova methods in different hydrolithologies



6.3 ESTIMATING SUSTAINABLE BOREHOLE YIELDS

The sustainable yield of a borehole is not obtained from conventional test pump interpretations. These interpretations are used to establish the hydraulic properties of the aquifer. Presented in this section are six methods for estimating the sustainable yield of a borehole, some of which require a transmissivity value and other parameters which are obtained from test pump curves. Two of the methods have been developed during the course of this study, both of which are based on the Cooper-Jacob approximation of the Theis equation. Although the remaining four methods have been previously described, none of them were given titles, which necessitated the naming of them for the purposes of this report.

6.3.1 The maximum drawdown method (Enslin and Bredenkamp, 1963)

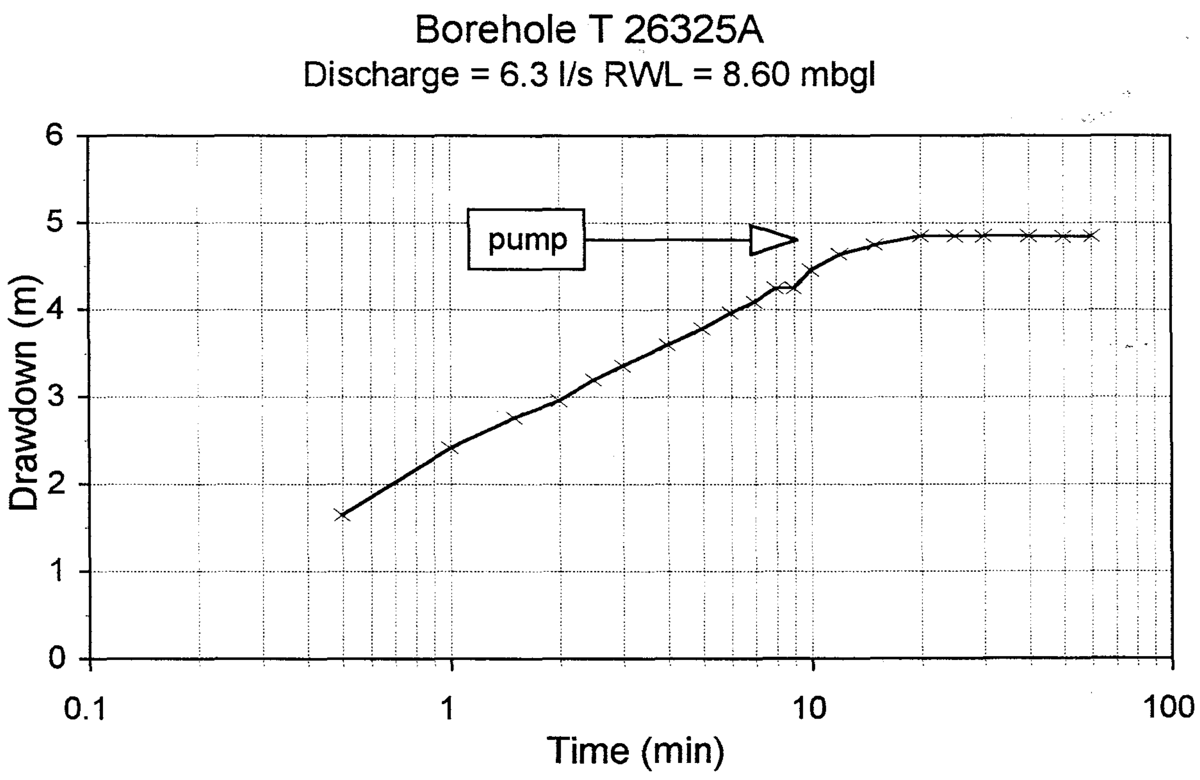
This method establishes the borehole yield from the maximum drawdown test, and is probably the most common type of pump test carried out in South Africa. Most of the test pumped boreholes in the former "homelands" and on the farms throughout South Africa have been tested using this method. The method involves placing the pump near the bottom of the borehole and pumping at a high rate until the water in the borehole is drawn down to the pump. Thereafter the abstraction rate is reduced until the water level in the borehole rises above the pump. The recommended yield for an 8 - 12 hour pumping day is usually taken as 60% of the highest yield a borehole can give without the water level in the borehole returning to the pump after 4 - 12 hours of pumping. The former Cape Provincial Administration's pump test team in the Eastern Cape Province recommend that 65% of the borehole's yield be taken as the production yield rather than the commonly used 60% (Jonker, pers comm.). The duration of the test varies, but it is commonly carried out for 4 - 12 hours, and contractors seldom take a time series of water levels.

This method was evaluated by assessing the performance of three boreholes whose daily abstraction rates were determined by the maximum drawdown method. The boreholes are currently pumped between five to seven days a week for about 12 hours per day. They are located in a broad valley near the perennial Swart Kei River in the Queenstown area of the Eastern Cape Province, and they penetrate fractured Karoo aquifers. Although the depths of the main water strikes were not recorded, it was common practice for the relevant former "homeland" department to place the pumps near the main water strike.

Borehole T 26325A

Depth:	35 m
Water strikes:	Unknown
Pump intake:	14 m
Tested yield:	11.4 l/s (after a nine hour maximum drawdown test)
Recommended yield using the maximum drawdown method:	6.8 l/s
Current pumping rate:	6.3 l/s (prior to the water in the borehole reaching the pump)
Percentage of tested yield:	55%
Current pumping duration:	10 - 12 hours per day Monday - Friday
Comments:	The water in the borehole reaches the pump after 20 minutes of pumping at the rate recommended by the maximum drawdown method. Without knowing the depth of the water strikes it is not possible to say whether the pump was set at the most suitable depth.

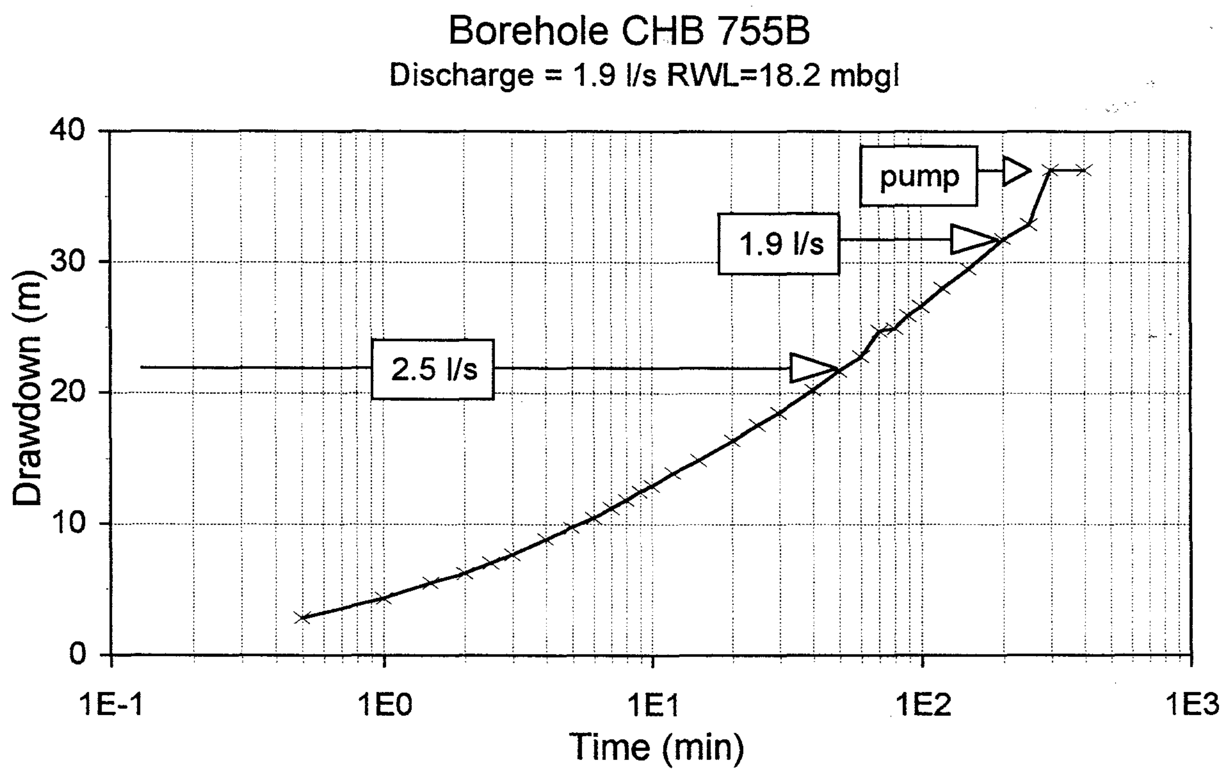
Figure 6.7 **Drawdown on borehole T 26325A at current production rate**
(The depth of the pump intake is indicated by the text box)



Borehole CHB 755B

Depth:	121 m
Water strikes:	51 m & 78 m
Pump intake:	55 m
Tested yield:	3.0 l/s (after a nine hour maximum drawdown test)
Recommended yield using the maximum drawdown method:	1.8 l/s
Current pumping rate:	1.9 l/s (prior to the water in the borehole reaching the pump)
Percentage of tested yield:	63%
Current pumping duration:	13 hours per day Monday - Friday
Comments:	The water in the borehole reaches the pump after 300 minutes of pumping at the rate recommended by the maximum drawdown method. The pump intake should probably have been set near the second water strike, even though the first water strike may have been the higher yielding one.

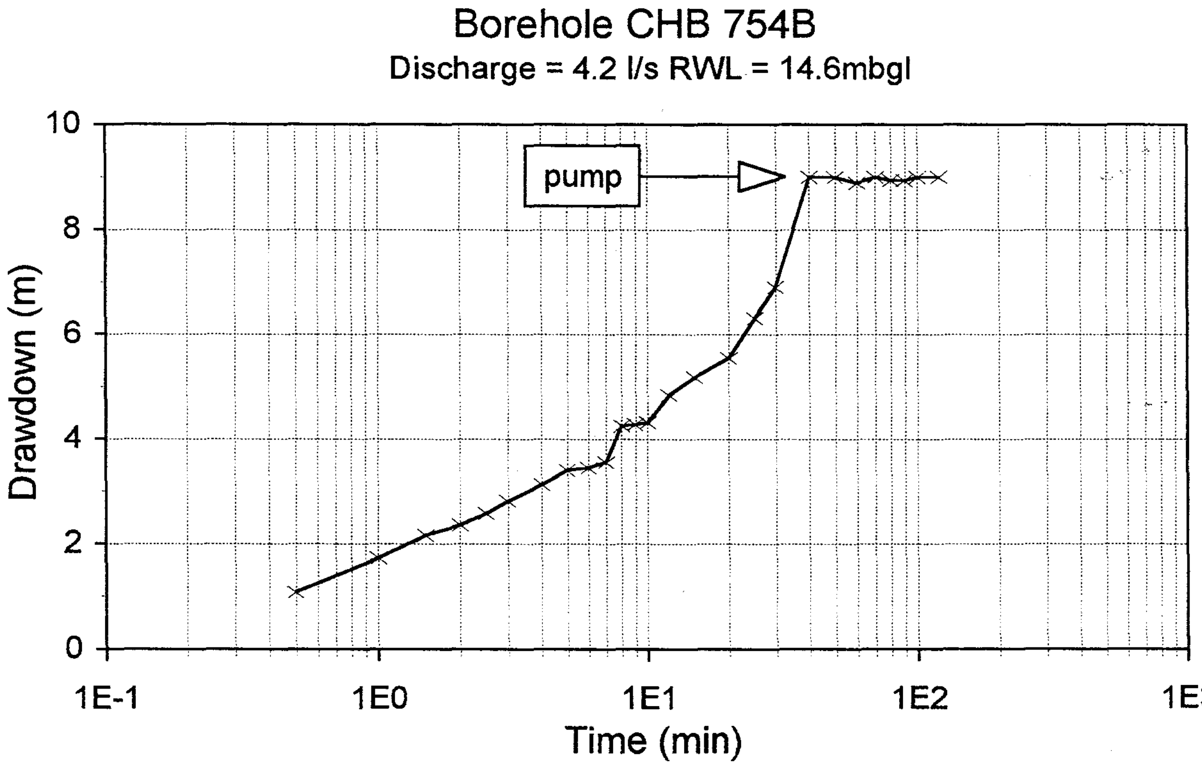
Figure 6.8 Drawdown on borehole CHB 755B at current production rate
(The depth of the pump intake is indicated by the text box)



Borehole CHB 754B

Depth:	54 m
Water strikes :	7 m & 24 m
Pump intake:	23.6 m
Tested yield:	5.6 l/s (after a nine hour maximum drawdown test)
Recommended yield using the maximum drawdown method:	3.4 l/s
Current pumping rate:	4.2 l/s (prior to the water in the borehole reaching the pump)
Percentage of tested yield:	75%
Current pumping duration:	12 hours per day Monday - Friday
Comments:	The water in the borehole reaches the pump after 40 minutes of pumping at 0.8 l/s greater than is commonly recommended by the maximum drawdown method.

Figure 6.9 Drawdown on borehole CHB 754B at current production rate
(The depth of the pump intake is indicated by the text box)



In all three cases the maximum drawdown method over-estimated the sustainable yield of the boreholes, although in the case of Borehole CHB 754B, the current production rate is slightly higher than what is usually recommended by this method. Enslin and Bredenkamp (1963), commenting on maximum drawdown tests in secondary aquifers, state that where equilibrium (or a constant drawdown) is reached before the end of the pumping test, the yields measured are the reliable indicators of the long term potentials of those boreholes, and that these yields equal the safe yield of the borehole if storage and recharge are not the limiting factors. Because borehole water level readings are seldom taken during this test, it is usually not possible to establish whether equilibrium has been reached.

In the three examples presented, it is unlikely that recharge or storage limits the sustainable yield of these boreholes. Recharge to the aquifer in which these boreholes are located was determined through an inverse modelling exercise under steady state conditions, using the finite difference model, MODFLOW. The annual recharge was found to be in the order of 8 mm (Sami and Murray, 1995), which translates to approximately 400 000 m^3 per annum for the whole basin in which these boreholes are located. Due to the size of the basin and because other, disused boreholes in the basin are water bearing, it is likely that storage is not the limiting factor either, even if the aquifer has a low average storativity.

The unsustainable high initial yields of these boreholes suggest the aquifer is characterised by localised, high permeability fracture zones, which are supplied by a matrix with a lower permeability. It would appear that the sustainable yield of these boreholes are controlled by matrix transmissivity rather than fracture transmissivity, aquifer recharge or storage. In all three cases, the high, unsustainable discharges at the end of the nine hour pumping tests reflect the transmissivity of the fractures. For equilibrium to be reached which reflects the hydraulic characteristics of the matrix, the test should have continued for a much longer period.

The above examples highlight the limitations of the maximum drawdown method. These limitations include:

- This test is usually not carried out for a sufficient duration to recognise the consequences of lower permeability boundaries. Such boundaries may consist of a low permeability matrix which supplies water to the fractures, or a lower permeability formation located laterally from the fracture zone in which the borehole is located.

- There is no justification for assuming 60% or 65% of the borehole's yield after four to twelve hours of pumping will equate to the borehole's sustainable yield.

- This method considers aquifer permeability only, and therefore a borehole's sustainable yield could be over estimated if aquifer recharge or storage controlled the sustainable yield of the borehole.

Based on the conceptual limitations and failure of the maximum drawdown method in the cases studied, this method was not considered for further study.

6.3.2 The recovery test method (Kirchner, 1991)

This method involves calculating the maximum number of hours a borehole should be pumped each day at the tested rate, and it is based on the time it takes for the water level in a pumped borehole to return to the original rest water level (prior to pumping). Borehole water level measurements during the recovery period following a constant discharge pump test are plotted on semi-log graph paper against the time since pumping began (t), divided by the time since pumping was stopped (t').

The following formula is then used to determine the maximum number of hours (h) a borehole should be pumped for each day, at the pumping rate of the preceding test:

$$h = 24 - (24/x) \qquad \text{eq.6.8}$$

where:

x = the x-axis intercept of the residual drawdown versus recovery plot (t/t') on semi-log graph paper after a constant discharge pumping test (Figure 6.10). Residual drawdown is the water level in a borehole after pumping has ceased.

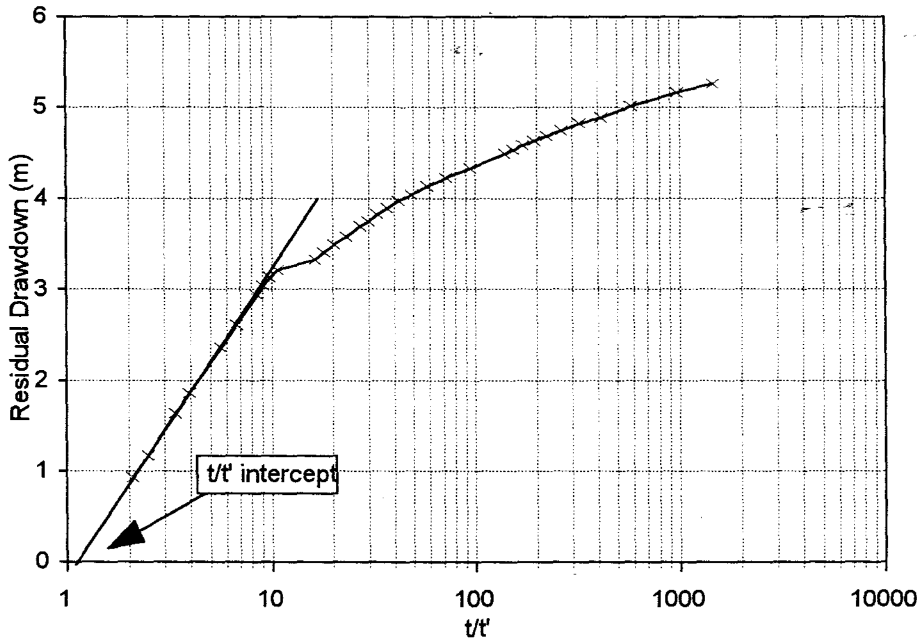
Theoretically zero residual drawdown should occur at t/t' = 2 if the abstraction rate equals lateral recharge (Kirchner, 1991). In this case the recovery time for the borehole is equal to the preceding pumping time and a 12 hour pumping day can be maintained. A more rapid recovery may be observed if either vertical recharge has occurred or if storativity is different during pumping and recovery due to air entrapment or elastic deformation of the aquifer (Driscoll, 1986). A longer recovery time or incomplete recovery would indicate a limited extent of the aquifer or lower permeability boundaries.

A major problem in applying the recovery method is when incomplete or rapid recovery is experienced. Recovery readings are seldom taken for a longer period than the pumping period, that is beyond t/t' = 2, hence extrapolations are necessary. Extrapolations can produce non-unique t/t' intercepts, which may have serious implications for yield derivations. For example, if intercepts could fall between 1.01 and 1.1 from a pumping rate of 4 l/s, which is a very plausible range given the standard error of slope extrapolations, yields of 3.4 to 31.4 m^3/day would be calculated. Extrapolations may also produce a t/t' value which is less than one, which gives a negative yield recommendation using equation 6.8. Under these circumstances it does not necessarily mean that the borehole cannot yield anything at all on a sustainable basis. Rather it indicates that partial dewatering of the aquifer took place during the constant discharge test, or that the aquifer is bounded by formations with relatively low permeabilities. While these may be good reasons to be cautious in recommending a long term abstraction rate, they are not reasons to abandon the borehole altogether.

In cases where rapid recovery occurs due to leakage from overlying material or variations in storativity, relatively high t/t' values may be obtained. This results in the calculation of large yield values. Since the extent of storage in these horizons is not taken into account, the sustainability of these yields would be uncertain.

It is also necessary to examine the assumption that recovery time is related to the preceding pumping rate. Could a borehole pumped at a low rate relative to its potential require just as long to recover than if it were pumped at a higher rate? If a low rate was selected, a low pressure gradient would be induced in the fractures, which would limit their rate of replenishment from the surrounding matrix. Consequently, similar t/t' intercept values may be obtained irrespective of the preceding pumping rate. The implication is that a much lower yield value would be calculated relative to that which would have been calculated from a high pumping rate recovery test. The application of this method should possibly be restricted to tests where the pumping rate is close to the borehole's capacity and where the recovery is complete.

Figure 6.10 Recovery curve showing t/t' intercept



6.3.3 The transmissivity method

The method is described in unpublished groundwater course notes by the Canadian International Development Agency (CIDA), and has been used by the Geological Survey in Swaziland (Ngwenya, pers comm.). Swaziland's Geological Survey carries out twenty four hour constant discharge tests on boreholes to be equipped with motorised pumps and eight hour tests on boreholes to be equipped with handpumps or windmills (Ngwenya, pers comm.).

An approximate daily production yield in m^3/day (Q) is calculated using the following formula:

$$Q = 0.068\ T\ s \qquad \text{eq.6.9}$$

where:

T = transmissivity (m^2/day)
s = available drawdown (m)

CIDA recommend transmissivity be calculated using Jacob's straight line recovery method (Todd, 1980) and available drawdown be taken as the distance between the rest water level and the main water strike.

After unsuccessfully trying to establish the theoretical basis of this equation, it was felt that the only possible justification could have been that the maximum recommended drawdown in primary aquifers is commonly taken as 68% of the saturated thickness (Driscoll, 1986). Because no other theoretical basis for this equation could be established, it was not considered for further study. The hypothetical example given below illustrates the sensitivity of this method to available drawdown, and the weakness of this dependancy in fractured rock aquifers.

Consider a fractured rock aquifer which is characterised by a steeply dipping, permeable fracture zone with low porosity, and a porous weathered zone which serves as the aquifer's storage reservoir. Two closely spaced boreholes intersect the fracture zone at different depths. When test pumped, they give similar transmissivity values. The available drawdown in the two boreholes differ because the distance between their rest water levels and their water strikes differ. Because the groundwater resource available to the boreholes is much the same (similar permeability, storage and recharge), the sustainable yields of the boreholes would also be much the same. However, in applying the transmissivity method, the borehole with the deep water strike would give a far greater yield than the borehole with the shallow water strike.

6.3.4 Methods based on the Theis equation

Three methods which are based on the Cooper-Jacob approximation of the Theis equation are presented. These methods can only be used if the constant discharge test is carried out in accordance with standard test pump procedures (Weaver, 1993).

In order to calculate the maximum pumping rate which would maintain a drawdown (s) above a specific point, after a long duration of pumping, the Cooper-Jacob equation can be defined as:

$$\mathbf{Q = 4 \pi T s / [2.3 \log (2.25 T t / r^2 S)]} \quad \text{eq.6.10}$$

where:

Q	= sustainable yield (m^3/day)
T	= transmissivity (m^2/day)
s	= available drawdown (m)
t	= pumping time (days)
r	= radius of the borehole (m)
S	= storativity

Note that the sustainable yield (Q) obtained in equation 6.10 is not very sensitive to the logged variables in the equation. Errors in the S and t estimate therefore do not significantly affect the Q-value. The equation however, is sensitive to transmissivity and available drawdown, which makes the accurate determination of these parameters critical. Appendix 3 lists S-values obtained from South African aquifers. These values should be viewed as a guideline for use in equation 6.10 if no local values are available. Equation 6.10 is used in different ways in the following three borehole yield assessment methods.

6.3.4.1 The late-T method

This method, described by Kirchner and Van Tonder (1995), uses equation 6.10 to recommend a daily discharge, Q.

Kirchner and Van Tonder (1995) recommend that T be estimated from the semi-log slope of the time-drawdown curve using data from the latter (late-time) part of the curve, when evaluating fractured rock aquifers (Figure 3.8 and 6.12). This segment of the curve reflects the rate of leakage from the matrix to the fractures, or it indicates that the radius of influence incorporates zones of lower T-values. The lower T-values will be referred to as the matrix-T or T_m, whereas the higher T-value, calculated from the early-time data, will be referred to as the fracture-T or T_f.

The matrix storativity (S_m) is used in the Cooper-Jacob equation (eq.6.10). S_m is usually greater than S_f (fracture storativity), and therefore has greater influence on the long-term exploitation potential of the aquifer (Vegter, 1995).

The pumping time (t) is taken as one year. By using such a long time without any recharge, Kirchner and Van Tonder (1995) believe influences such as boundary conditions will be cancelled out. While this assumption may not hold in many cases, it is not possible to predict barrier boundaries which would be encountered beyond the duration of the pump test and therefore it makes sense to use a high t-value.

Kirchner and Van Tonder (1995) recommend the available drawdown, a sensitive parameter in equation 6.10, be taken as the distance from the rest water level to the main water strike in the borehole. The assumption that a borehole's sustainable yield is directly proportional to this distance, is questioned in the following two hypothetical examples.

Example 1:
Two boreholes which penetrate a fractured Karoo aquifer are located about 4 m apart, perpendicular to a steeply dipping dyke. The following hydraulic conditions prevail:

Matrix storativity:		0.001
Late-time transmissivity:		5 m^2/day
Rest water level:		10 m.b.g.l.
Main water strike -	B/h 1:	50 m.b.g.l. (ie. Available drawdown = 40 m)
	B/h 2:	30 m.b.g.l. (ie. Available drawdown = 20 m)

Using the late-T method, a yield of 124 m^3/day is obtained for Borehole 1, and 62 m^3/day for Borehole 2. Although the sustainable yield of the borehole may be influenced by the depth of the main water strike, because with increasing depth of the water strike the cone of depression can have a greater area of influence, it is clearly unreasonable to assume that these factors are directly proportional. If the main storage component of the aquifer was a narrow, near surface band of weathered rock, the depth of the water strikes below the base of this zone should not significantly affect the sustainable yields of the boreholes.

Example 2:
A borehole intersects a deep water strike in an unconfined aquifer with a high storage capacity. The late-T method assumes that the entire available drawdown can be pumped in a given year, thus assuming that

annual recharge will result in its complete replenishment. Should the aquifer not be fully recharged, the water table would be lower than when pumping first started, and the available drawdown would be less than the initial available drawdown. The drop in the available drawdown would be in proportion to the volume of water removed from storage. To continue pumping at year one's rate could result in the water strike being reached during, rather than at the end of year two, thereby indicating that the yield predicted by the late -T method is not sustainable. If recharge cannot replenish the water held in storage over the chosen recharge period, this method may give an exaggerated yield recommendation.

The concept of applying the transmissivity that reflects flow from the matrix to the fractures in the double porosity model has a good theoretical basis, because it is the matrix with its high storage capacity that supports the abstraction between recharge events. Equation 6.10 is however highly sensitive to available drawdown, a parameter which should not necessarily be based on the distance between the rest water level and the main water strike.

A drawback in the application of this method is that it relies on knowing the depth of the main water strike. This is often a problem as a result of unreliable or non-existent borehole records.

6.3.4.2 The drawdown-to-boundary method

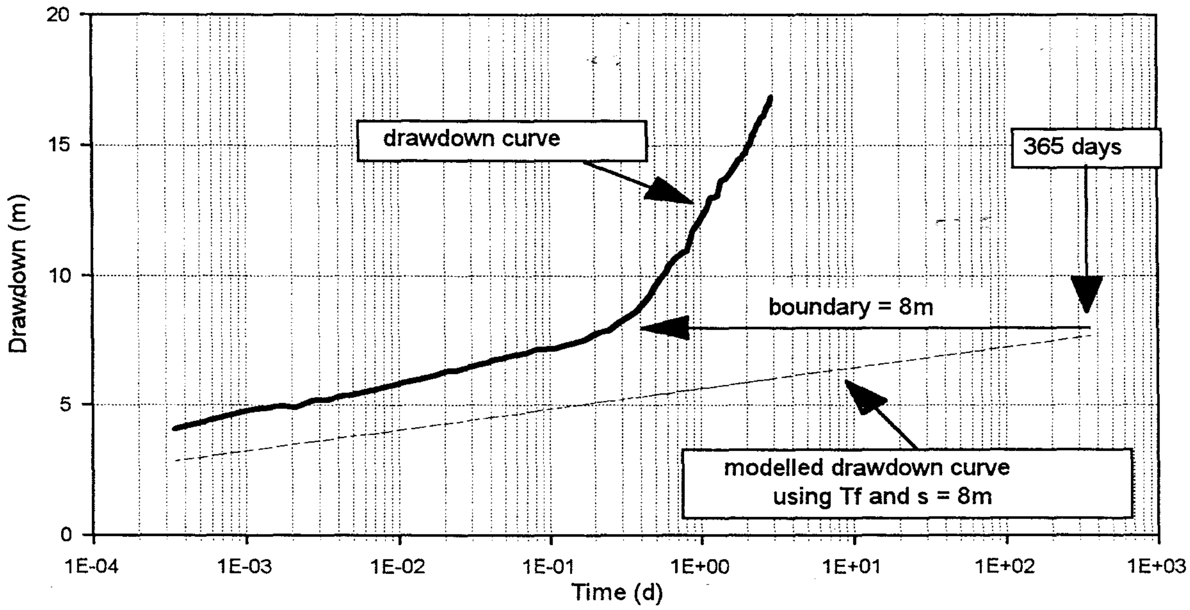
This newly developed method has been adapted from a borehole yield assessment approach used by A. Woodford (Directorate of Geohydrology, DWAF). It is referred to as the drawdown-to-boundary method because emphasis is on determining the maximum drawdown permitted in order to prevent the dewatering effects that may result once a low permeability boundary is encountered. As with the late-T method, equation 6.10 is used to recommend a daily discharge, Q.

The available drawdown, s in equation 6.10, is limited to the point at which an inflection in the semi-log slope of the time-drawdown curve is identified (8 m in Figure 6.11 and 4.5 m in Figure 6.12). Hence, if a sharp increase in the rate of drawdown is observed, the height of the rest water level above this point is taken as the available drawdown. The aim of this method is to determine an abstraction rate that will restrict the drawdown at the end of a pumping year to the inflection point. The modelled drawdown curve in Figure 6.11, which is derived from equation 6.10 using T_f and s = 8 m, reflects this pumping rate.

Woodford (pers comm.) recommends that the s-value be taken as the thickness of the weathered formation below the piezometric level or water table in aquifers which derive most of their storage from this zone. By limiting the long term drawdown to the base of the weathered zone, the risk of dewatering the storage component of the aquifer is reduced.

Fracture transmissivity (T_f in Figure 6.12) and fracture storativity values should be used in equation 6.10 because they control the rate of drawdown during the early, pre-boundary pumping times. Vegter (1995) suggests that storativity values for fractured rocks are at least an order of magnitude less than that of the porous, decomposed and disintegrated rock, regardless of fracture density. Thus an S_f value which is an order of magnitude less than regional S_m values can be used in equation 6.10.

Figure 6.11 Modelled drawdown curve based on the drawdown-to-boundary method



An advantage of the drawdown-to-boundary method is that it aims to limit the long-term drawdown in the borehole to a level at which a hydraulic boundary is encountered. As stated earlier in this chapter, such boundaries may be caused by different geological conditions. A boundary may consist of a geological barrier which delineates the lateral extent of the aquifer; it may consist of a geological formation with lower permeability, or zones within a formation of lower permeability; and it may consist of a matrix of lower permeability than the fractured parts of the aquifer.

A possible drawback of the drawdown-to-boundary method is that it does not consider permeability of the material which forms the boundary. Limiting drawdown according to the nearest hydraulic boundary does not take into account that such a boundary may not be impermeable but may only represent reduced permeabilities or a reduced rate of vertical leakage in double porosity or semi-confined formations. These may bear additional water under higher pressure gradients when stressed and would therefore not be utilised under drawdowns maintained by the prescribed yield. Where the aquifer is highly heterogeneous or exhibits a delayed yield response, the rapid appearance of such an apparent boundary may lead to an attempt to maintain too small a drawdown, thereby resulting in overly conservative yield estimates.

6.3.4.3 The distance-to-boundary method

The above name has been given to this newly developed method because it requires that the theoretical radius of influence at the hydraulic boundary be determined. The method employs a modification to the Cooper-Jacob equation (eq.6.10) where r is the radius of influence in the aquifer when boundary conditions are encountered. When an inflection in the semi-log slope of the time-drawdown curve is identified at time t, the radius of influence (r) at that time is calculated using equation 6.7 by solving for:

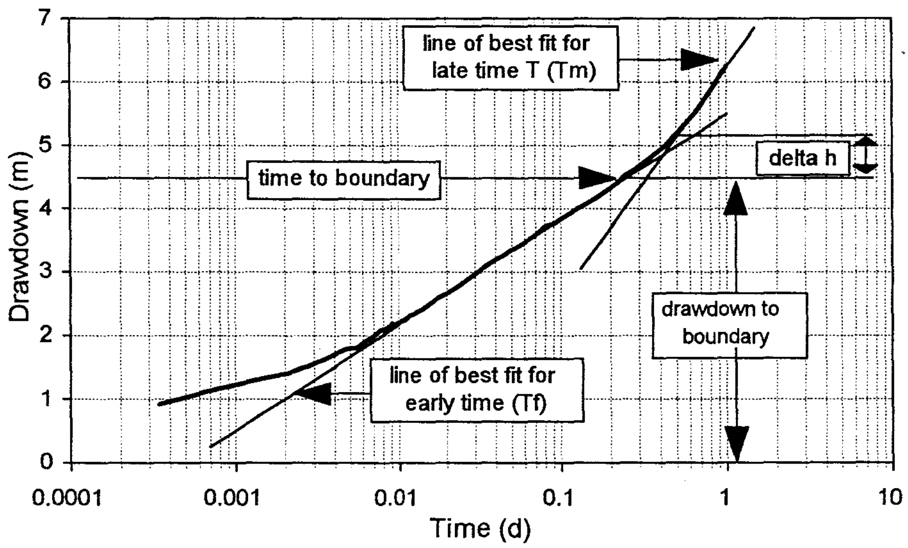
$$r^2 = 2.25\ T\ t\ /\ S \qquad \text{eq.6.11}$$

The point at which the early-time slope departs from the drawdown curve indicates the time a hydraulic boundary was encountered, and may be taken as the t-value (Figure 6.12). Again, it is important to note that this break in slope might not represent a true physical boundary to flow, but may represent a point in time at which the permeability of major fractures no longer controls a borehole's discharge-drawdown relationship in double porosity fractured rock systems. From this identified point in time a borehole's discharge is predominantly controlled by the rate at which water can leak into the main fractures from the surrounding rock matrix or from smaller micro-fractures.

Using this distance (r), equation 6.10 is used to calculate the pumping rate (Q) that can be sustained over the long-term (e.g. t = 365 days) while maintaining a negligible drawdown, Δh at distance r. The Δh value, which represents the drawdown during the transition from early- to late-time conditions (Figure 6.12), is substituted for s in equation 6.10.

The value r in equation 6.11 should be obtained using T_f and S_f because the fracture transmissivity and storativity control the rate of drawdown during early pumping times, before the boundary is encountered. In the calculation of Q in equation 6.10, T_f and S_m should be used since long term yield is controlled by the rate at which water stored in the matrix S_m can be released to the permeable fractures T_f.

Figure 6.12 Distance to boundary values



The concept of restricting the maximum abstraction so that significant drawdown is limited in extent to the theoretical distance of an observed boundary, seems appropriate in aquifers which are characterised by boundary effects. A drawback in the application of the distance-to-boundary method is that a Δh value may not be easy to obtain, for example where delayed yield or double porosity effects are experienced (Figure 6.3). An acceptable Δh value is essential when applying the distance-to-boundary method because of the sensitivity of Q in equation 6.10 to available drawdown (Δh in this case). Examples from Karoo aquifers indicate that a maximum Δh value of 1 m should be employed.

6.4 CONCLUSIONS

Four borehole yield assessment methods which are appropriate to secondary aquifers have been identified for further study. Three of the methods are based on the Theis transient state equation, and one is based on the recovery curve which follows the constant discharge test. Chapter 7 compares these methods and the aquifer yield assessment methods to established yields from production boreholes.

7. A COMPARISON OF BOREHOLE YIELD ASSESSMENT METHODS

7.1 INTRODUCTION

In order to test the borehole yield assessment methods described in the previous chapters, it was necessary to compare the yields obtained from these methods to established yields from production boreholes. As mentioned in Chapter 1, this posed the following three problems:

i) Establishing a borehole's maximum sustainable daily yield

It is difficult to determine a borehole's maximum, sustainable daily yield, even if abstraction, water level and rainfall data exists. In order to obtain this yield, the following conditions would be necessary: The water level in a borehole should not be affected by other production boreholes; The borehole should not be pumped at a low rate with respect to its potential, as this would not indicate the maximum sustainable yield; The borehole should be pumped at a rate greater than its potential, so that its unsustainable yield is known (the borehole would not necessarily need to have failed, as water level data monitored over a sufficient period can indicate whether the borehole's yield is sustainable); The abstraction, water level and rainfall data should have been monitored for a sufficiently long period so that the effects of recharge and storage on the borehole's sustainable yield can be established. These conditions are extremely rare, and therefore, for the purpose of this study it was necessary to compare the borehole yield assessment methods to estimates of the probable sustainable yield range of each borehole.

ii) Obtaining data from which to estimate a borehole's maximum sustainable daily yield

It was difficult to obtain data from which to estimate a borehole's maximum sustainable daily yield. In the first instance, few individuals or institutions who manage groundwater resources keep suitable records (including the original test pump data), or were willing to impart with them. Secondly, where records were available, they seldom consisted of sufficient information from which an estimate of the borehole's sustainable yield could be made.

Groundwater consulting firms, DWAF, a water board, research institutions, non governmental organisations, municipalities and a mining company were approached for borehole information which included geological logs, test pump data, abstraction data and monitored water level data. Out of the fifteen organisations approached, the following six responded: DWAF, the Council for Scientific and Industrial Research, the Institute for Groundwater Studies, PD Toens and Associates and the Tanzanyika Christian Refugee Services. Data was also available from the Institute for Water Research.

Most of the data received included information from wellfields where borehole interference is a problem. In such cases the extent of borehole interference was studied and where it seemed substantial, the data were not used. In some cases boreholes located in the upper most section of a wellfield were used because interference was assumed to be least there. At the end of this process fifteen cases were selected for study.

iii) The information required to apply the aquifer yield assessment methods would be difficult to obtain

In order to apply the aquifer yield assessment methods, aquifer parameters such as the area contributing to recharge, storativity, hydraulic gradient, etc., are required. This information was generally not available, and therefore it was estimated wherever possible. For example, aquifer thicknesses and storativity values were estimated from the borehole logs. In assessing the throughflow method, the transmissivity value obtained from the late-time segment of the drawdown curve (T_m) was used with the full width of the seepage face, which was usually estimated to be the width of the valley bottom. Another problem associated with verifying the aquifer yield assessment methods is that the requirements to apply these methods (for example that the aquifers be relatively small, or that the areas contributing to recharge be relatively small) were met in only three of the fifteen case studies. No more suitable case studies could be found after an extensive search for data.

Although too few case studies were collected to establish which method is most appropriate in specific hydrogeological environments, such as dual porosity aquifers, leaky aquifers, etc., the data presented below gives a good indication of which methods are generally most successful. A discussion of the methods in view of the case studies presented below, is given in the following chapter.

7.2 KAROO SEQUENCE AQUIFERS

Of the five boreholes studied, regular monitoring of abstraction and water level data was only carried out on two of them, namely those from Graaff Reinet in the Eastern Cape Province. Two of the remaining three boreholes were heavily over pumped by farmers and their yields had to be reduced dramatically. Estimates of their sustainable yields were made after considering their current production yields. The fifth borehole has been used by the Dewetsdorp municipality for years without signs of over abstraction.

Borehole GR 2

Location:	Graaff-Reinet, Eastern Cape Province, South Africa.	
Lithology:	Beaufort Group, Karoo Sequence.	
Geological log:	0 - 2 m	Calcareous sandy alluvium.
	2 - 10 m	Siltstone and shale.
	10 - 39 m	Sandstone
	39 - 44 m	Sandstone and shale.
	44 - 53 m	Sandstone.
Depth:	53 m	
Water strikes:	18 m - 4.4 l/s; 36 m - 3.4 l/s; 38 m - 3.0 l/s; 42 m - 17.2 l/s; 44 m - 11.0 l/s	
Final blow yield:	39 l/s	
Current use:	Municipal production borehole.	

Aquifer properties

T-early (m^2/d):	137
T-late (m^2/d):	47
T-recovery (m^2/d):	83
S_f (estimate):	0.0004
S_m (estimate):	0.004
t/t' intercept:	0.6
RWL-main water strike (m):	36*[1]
Dist.-boundary (m):	11
Time-boundary (d):	0.7
Δh (m):	1
Catchment area (km^2):	180
Recharge estimate (mm/a):	7*[2]
Abstractable % of recharge:	5
Aquifer thickness (m):	20
B/h success rate (%):	70
Years without recharge:	3
Aquifer width (m):	7000
Hydraulic gradient:	0.005

*[1] RWL = Rest water level
*[2] 2% of MAP

Borehole yield (m^3/d)

Recovery method:	0
Late-T method:	1010
Drawdown-boundary:	775
Distance-boundary:	436

Aquifer yield (m^3/d)

Recharge:	173
Storage:	460
Throughflow:	82

Current yield (m^3/d): 181

Failed at (m^3/d): 665

Discussion

The drawdown curve deviates from a straight line at about 19 hours (Figure 7.1), indicating that the cone of depression encountered a hydraulic boundary of lesser permeability. The recovery test (Figure 7.2) gave a residual drawdown of 3.88 m three days after the constant rate test was stopped.

Boreholes GR 2 and the following example, GR 1, are less than 800 m apart and penetrate a common aquifer which is also exploited by a third, lower yielding borehole. After assessing abstraction and borehole water level data, Smart (1994) estimated the sustainable yield of the wellfield to be 288 000

m^3/annum or 789 m^3 /day, and Woodford (1992) recommended that this borehole be pumped at 360m^3/day. Abstraction records show that borehole GR 2 was pumped at an average yield of 665 m^3/day for the first two years of production. The water level in the borehole dropped by about 10 m (Figure 7.3) and the yield was reduced to an average of 181 m^3/day. With two other boreholes in the wellfield being used on a regular basis, GR 2 could not sustain a pumping rate of 665 m^3/day. However, the rise in water level after the yield reduction indicates that a yield greater than 181 m^3/day could be sustained. If it was the only production borehole in the aquifer, its sustainable yield would likely be significantly greater than 181 m^3/day, and possibly even more than Woodford's recommended yield of 360 m^3/day. It is also likely that this borehole's sustainable yield is significantly less than Smart's aquifer's yield of 789 m^3/day, as it is improbable that a single borehole can abstract the full yield that the wellfield can supply.

The late-T method's yield of 1010 m^3/day is greater than the aquifer yield (Smart, 1994), and clearly over estimates the sustainable yield of this borehole. The drawdown-to-boundary method's yield of 775 m^3/day also appears to be too high, that is, if the 11m inflection point on the drawdown curve is used. If the thickness of the saturated weathered zone is used, which according to Woodford (pers comm.) is 6 m, a yield of 423 m^3/day is obtained. This appears to be a reasonable figure so long as no other boreholes within the wellfield were brought into production. Interestingly, the first inflection point on the drawdown curve at 6 m, corresponds to the thickness of the saturated weathered zone. The yield obtained using the distance-to-boundary method (436 m^3/day), is similar to the yield obtained using the drawdown-to-boundary method with an available drawdown value of 6 m. Given that the borehole showed incomplete recovery after the constant discharge test, and that the pumping rate of 665 m^3/day could not be sustained, the ± 430 m^3/day yields obtained from the distance-to-boundary method and drawdown-to-boundary method (using an s-value of 6 m) seem to be reasonable.

None of the aquifer yield assessment methods should be used. The recharge method can not be applied because of the large catchment area above the borehole. Although a reasonable yield is obtained using the storage method (460 m^3/day), it should not be considered as a reliable assessment of the borehole's potential because the size, thickness and storativity of the aquifer is not known. The throughflow method can not be applied because it is unreasonable to assume that the late-time transmissivity value is representative of the whole seepage face.

References:

Smart, 1994. Mimosadale wellfield long term yield and future groundwater development at Graaff Reinet. DWAF Report GH 3836.

Steffen, Robertson and Kirsten, 1987. Wellfield development at Graaff-Reinet; Phase 1. Report CE 5892/1.

Steffen, Robertson and Kirsten, 1988. Wellfield development at Graaff-Reinet; Phase 2. Report CE 5892/2.

Steffen, Robertson and Kirsten, 1991 - 1993. Wellfield monitoring: Graaff-Reinet. Quarterly reports 164555/M.

Woodford, 1992. Comments on the Mimosadale wellfield for meeting 08/12/1992. Directorate of Geohydrology, DWAF.

Note: Boreholes GR1 and GR2 are boreholes 4 and 6 in the above mentioned reports.

Figure 7.1 Borehole GR 2: Constant discharge test

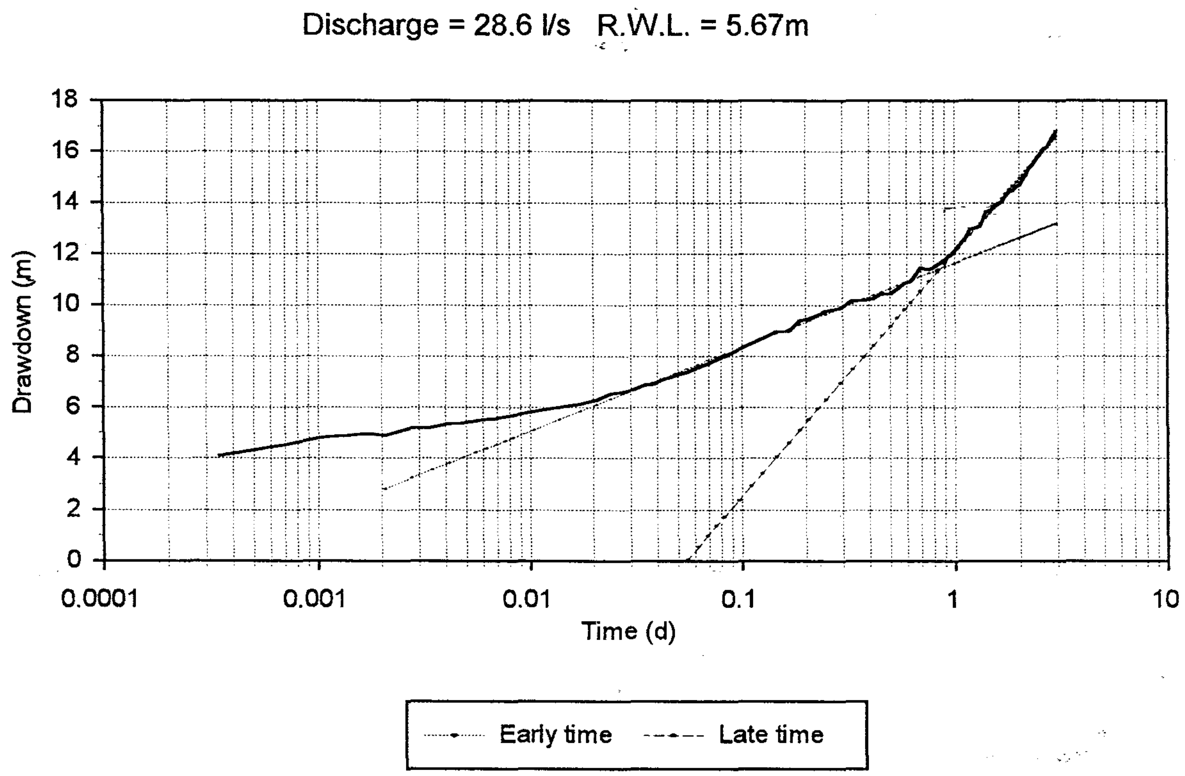


Figure 7.2 Borehole GR 2: Recovery test

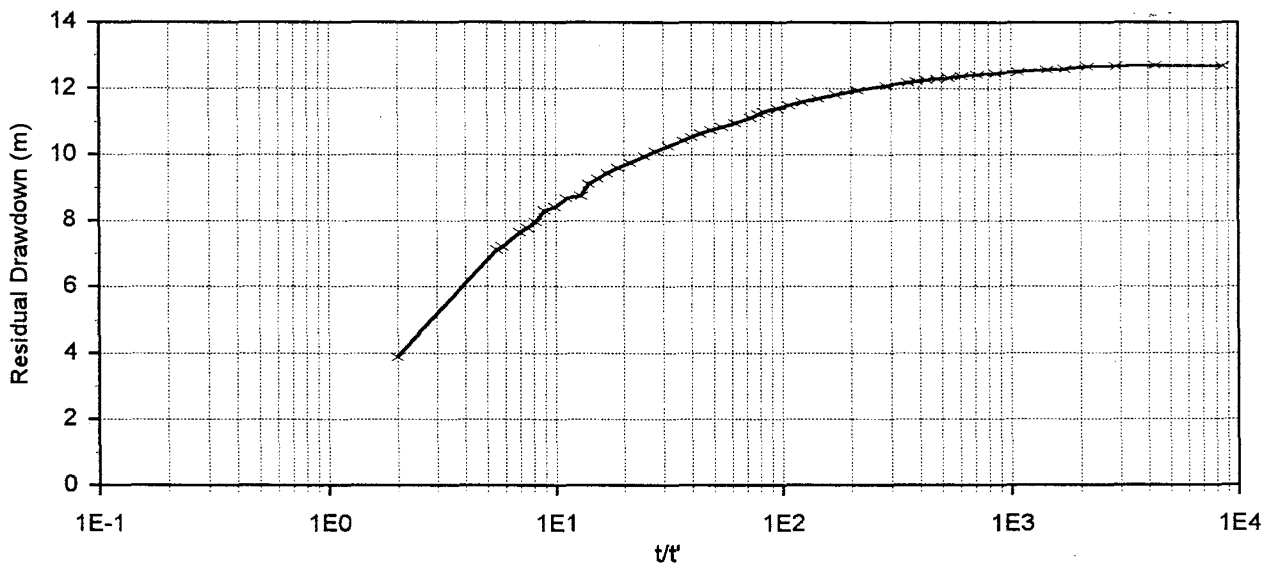
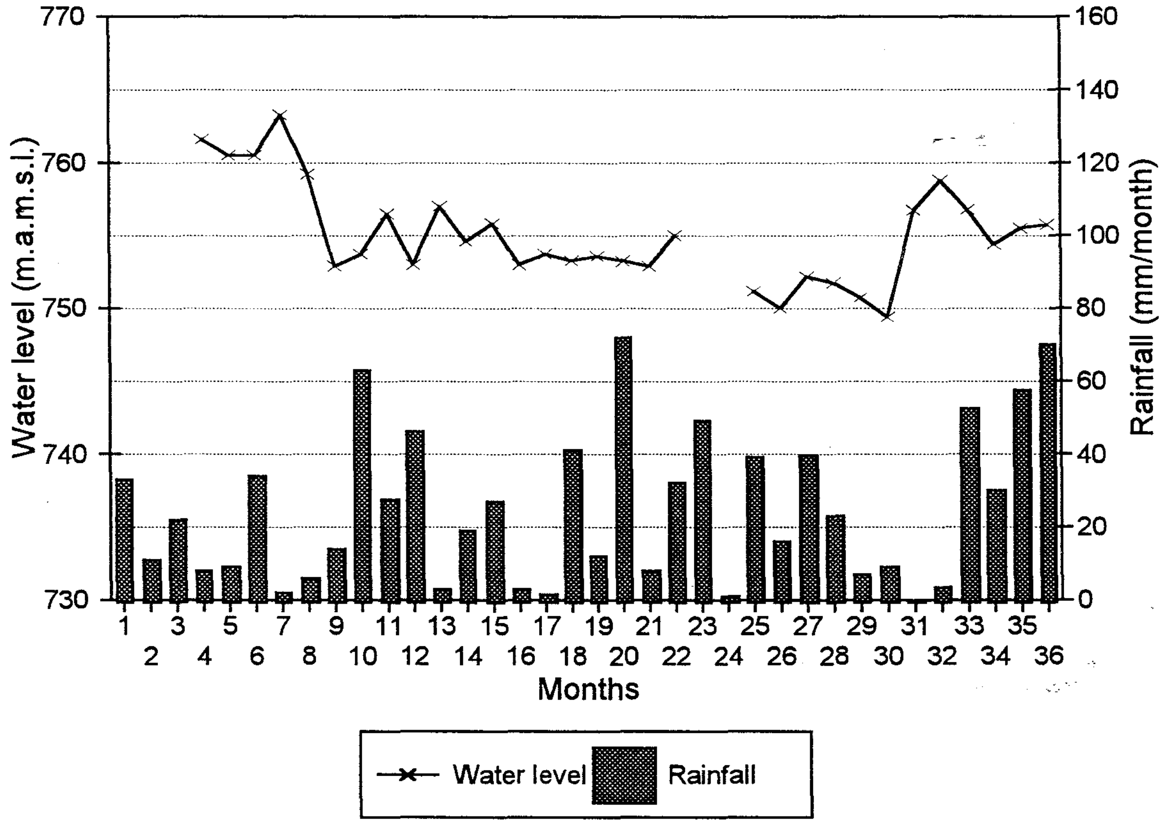


Figure 7.3 Borehole GR 2: Water level and rainfall data



Borehole GR 1

Location:	Same wellfield as borehole GR 1.	
Lithology:	Beaufort Group, Karoo Sequence.	
Geological log:	0 - 5.5 m	Top soil
	5.5 - 10 m	Weathered sandstone and boulders
	10 - 60 m	Sandstone with minor interbedded shale horizons.
Depth:	60 m	
Water strikes:	18 m, 24 m, 32 - 48 m. Main water strike at 24 m.	
Final blow yield:	20 l/s	
Current use:	Municipal production borehole.	

Aquifer properties

T-early (m^2/d):	208
T-late (m^2/d):	90
T-recovery (m^2/d):	-
S_f (estimate):	0.0004
S_m (estimate):	0.004
t/t' intercept:	-
RWL-main water strike (m):	15
Dist.-boundary (m):	5.5
Time-boundary (d):	0.1
Δh (m):	1
Catchment area (km^2):	180
Recharge estimate (mm/a):	7
Abstractable % of recharge:	5
Aquifer thickness (m):	20
B/h success rate (%):	70
Years without recharge:	3
Aquifer width (m):	7000
Hydraulic gradient:	0.005

Borehole yield (m^3/d)

Recovery method:	-
Late-T method:	782
Drawdown-boundary:	579
Distance-boundary:	444

Aquifer yield (m^3/d)

Recharge:	173
Storage:	460
Throughflow:	158

Current yield (m^3/d):	**393**
Failed at (m^3/d):	**735**

Discussion

The drawdown curve of this borehole shows that the late-time transmissivity is about half the early-time transmissivity, indicating the presence of a hydraulic boundary (Figure 7.4). The recovery data is unavailable. Like GR 2, the water level in this borehole declined steadily over the first two years of production with an average yield of 735 m^3/day (Figure 7.5). Once the yield was reduced to a daily average of about 400 m^3/day, the water level in the borehole began to stabilise.

If this was the only production borehole in the wellfield, the 579 m^3/day obtained from the drawdown-to-boundary method may not be unreasonable. The 782 m^3/day obtained from the late-T method seems to be an over estimation of the borehole's sustainable yield, considering that the aquifer's yield is believed to be 789 m^3/day (Smart, 1994), and the initial average yield of 735 m^3/day was too high. The distance-to-boundary method gives a reasonable yield, so long as a Δh value of 1 m is used. If the Δh had been obtained from the early- and late-time drawdown slopes, as shown in Figure 6.12, the value would have been smaller (± 0.5 m), and a significant underestimation of the borehole's sustainable yield would have been made. The aquifer yield assessment methods should not be applied for the same reasons given for borehole GR 2.

Figure 7.4 Borehole GR 1: Constant discharge test

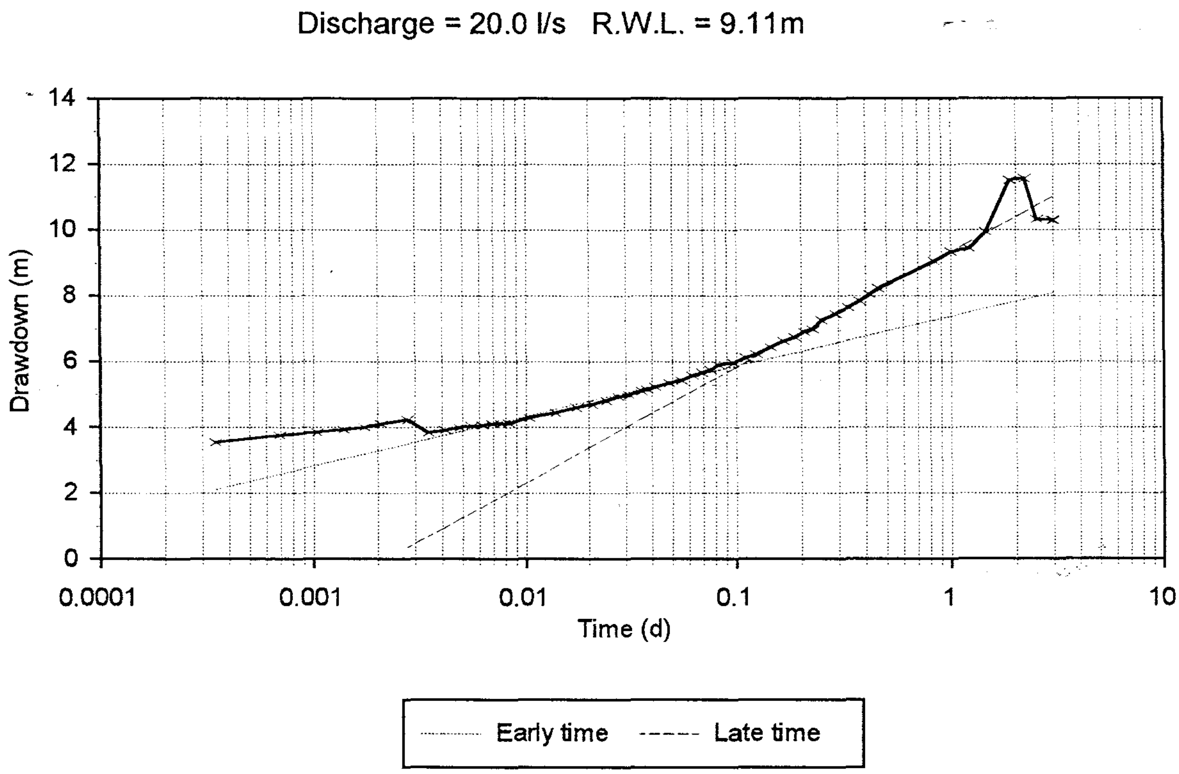
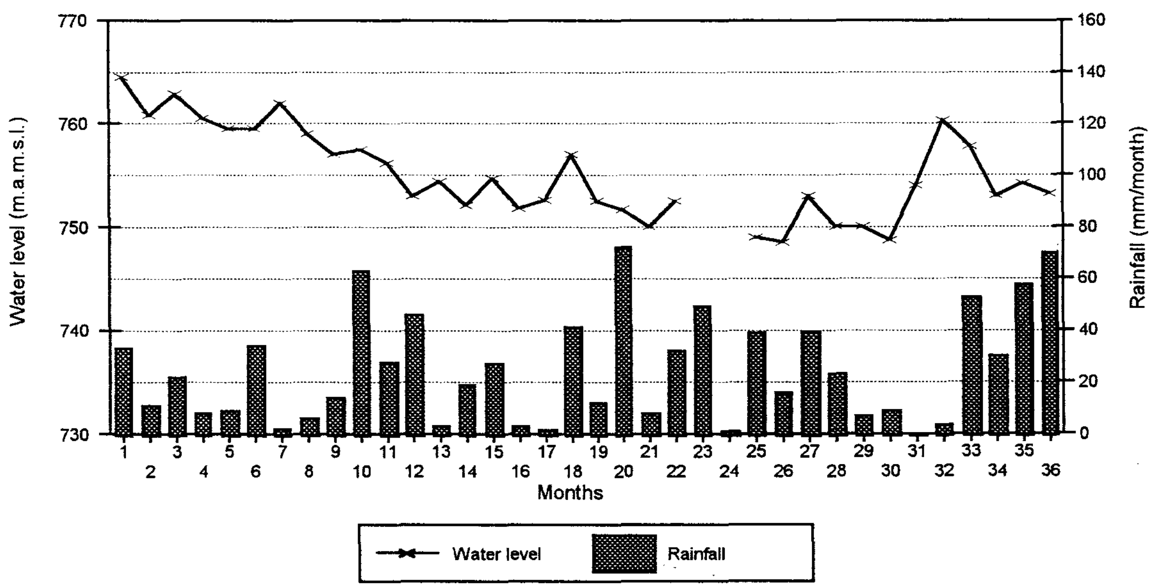


Figure 7.5 Borehole GR 1: Water level and rainfall data



Borehole BL1

Location:	Blinkwater, Eastern Cape Province, South Africa.
Lithology:	Balfour Formation, Beaufort Group, Karoo Sequence.
Geological log:	Interbedded sandstones, mudstones and shales.
Depth:	42 m
Water strikes:	Unknown.
Final blow yield:	Unknown.
Current use:	Agricultural production borehole.

Aquifer properties

T-early (m^2/d):	24
T-late (m^2/d):	11
T-recovery (m^2/d):	13
S_f (estimate):	0.00001
S_m (estimate):	0.0001
t/t' intercept:	1.05
RWL-main water strike (m):	-
Dist.-boundary (m):	4.7
Time-boundary (d):	0.3
Δh (m):	0.4
Catchment area (km^2):	52
Recharge (mm/a):	4.1*[1]
Abstractable % of recharge:	18
Aquifer thickness (m):	28
B/h success rate (%):	90
Years without recharge:	3
Aquifer width (m):	1 300
Hydraulic gradient:	0.005

*[1] Sami, 1994

Borehole yield (m^3/d)

Recovery method:	10
Late-T method:	-
Drawdown-boundary:	53
Distance-boundary:	25

Aquifer yield (m^3/d)

Recharge:	105
Storage:	22
Throughflow:	13

Current yield (m^3/d): 80

Failed at (m^3/d): 190

Discussion

This borehole, which shows boundary effects after 400 minutes of pumping (Figure 7.6), was initially pumped at about 190 m^3/day. This yield could not be maintained and the abstraction rate was reduced to about 80 m^3/day. As a long term production yield, 80 m^3/day also appears to be too high because the water level in the borehole is drawn down to the pump on a daily basis.

Because the depth of the main water strike is unknown, the late-T method cannot be used. Assuming, however, the main water strike was encountered 10 m before the bottom of the borehole, the late-T method would have given a yield of 160 m^3/day, which is clearly too high. Even if the main water strike was encountered 20 m before the bottom of the borehole, that is, 22 m below ground level, the late-T method's yield of 100 m^3/day, is too high. The drawdown-to-boundary method indicates that the production yield should be about 50 m^3/day, which is probably closer to the maximum sustainable yield than the current production yield. The distance-to-boundary method gives an acceptable yield, however it may be too conservative - only long term monitoring could establish this. Although there is insufficient information to establish the maximum sustainable yield of this borehole, the recovery method's yield of 10 m³/day is probably an underestimation of this borehole's potential. The aquifer yield assessment methods are not reliable because the necessary aquifer parameters were not clearly defined. The recharge and storage methods can be ruled out due to the large catchment area.

Figure 7.6 Borehole BL 1: Constant discharge test

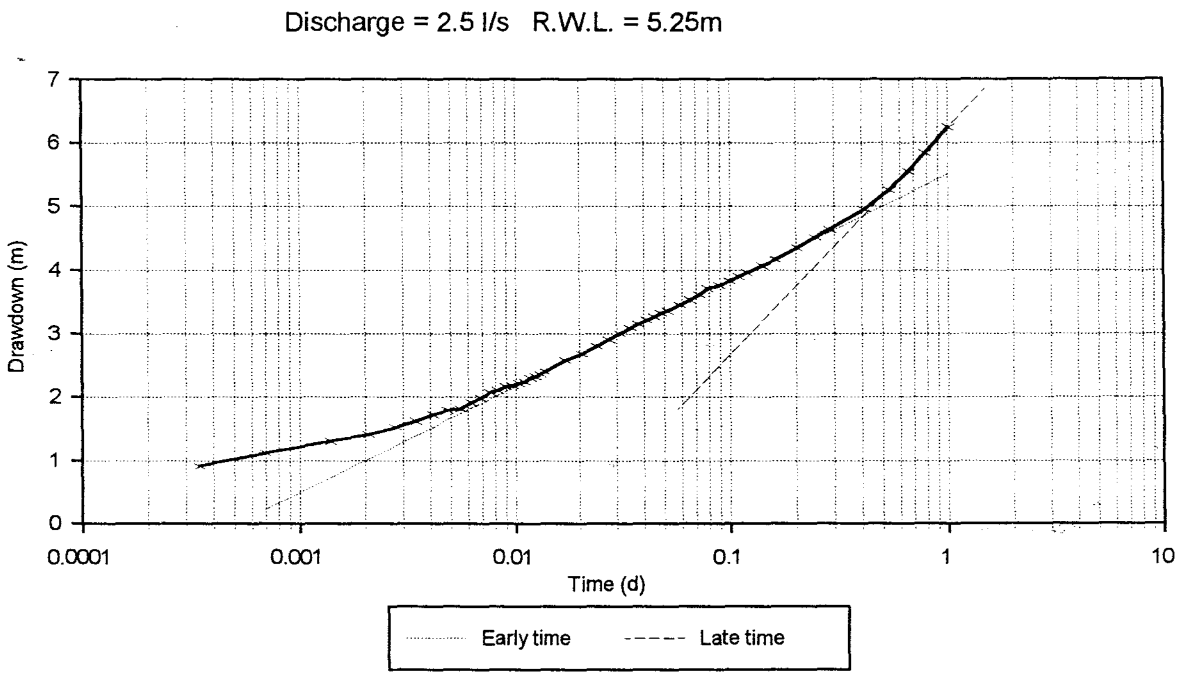
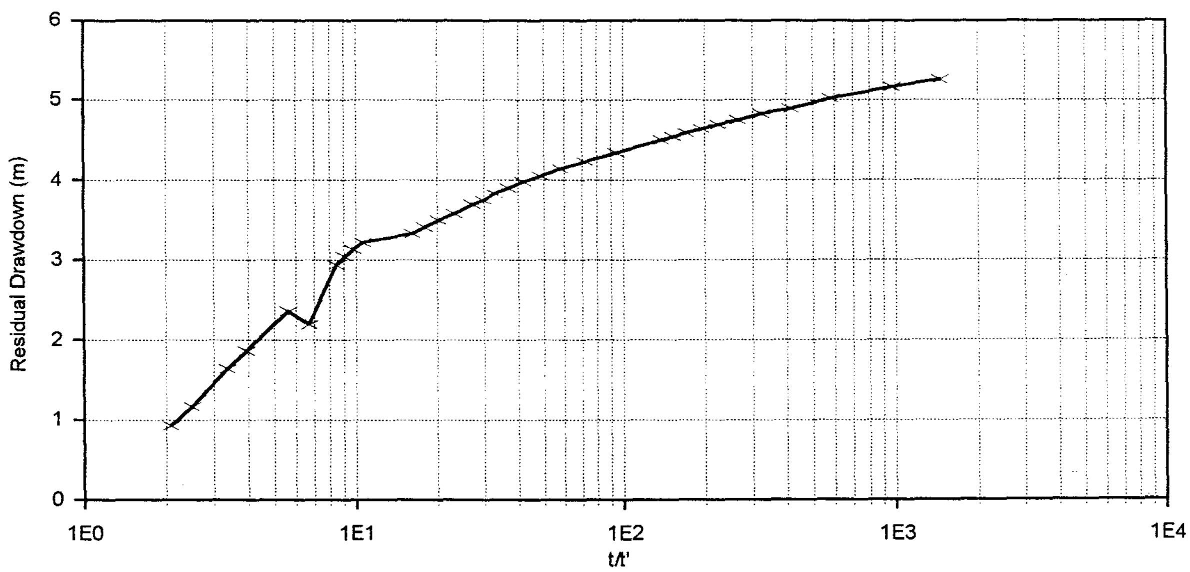


Figure 7.7 Borehole BL 1 Recovery test



Borehole BRG 7

Location:	Bedford, Eastern Cape Province, South Africa.
Lithology:	Middleton Formation, Beaufort Group, Karoo Sequence.
Geological log:	Unavailable. The Middleton Formation consists of interbedded sandstones and mudstones.
Depth:	Unknown.
Water strikes:	Unknown.
Final blow yield:	Unknown.
Current use:	Livestock.

Aquifer properties

T-early (m^2/d):	196
T-late (m^2/d):	56
T-recovery (m^2/d):	-
S_f:	0.0085*[1]
S_m:	0.011*[1]
t/t' intercept:	-
RWL-main water strike (m):	-
Dist.-boundary (m):	0.05
Time-boundary (d):	0.26
Δh (m):	0.02
Catchment area (km^2):	1
Recharge (mm/a):	4.1*[1]
Abstractable % of recharge:	65
Aquifer thickness (m):	-
B/h success rate (%):	70
Years without recharge:	3
Aquifer width (m):	250
Hydraulic gradient:	0.015

*[1] Data source: Institute for Water Research

Borehole yield (m^3/d)

Recovery method:	-
Late-T method:	-
Drawdown-boundary:	6
Distance-boundary:	7

Aquifer yield (m^3/d)

Recharge:	11
Storage:	-
Throughflow:	137

Current yield (m^3/d): 5 - 6

Failed at (m^3/d): 85 - 100

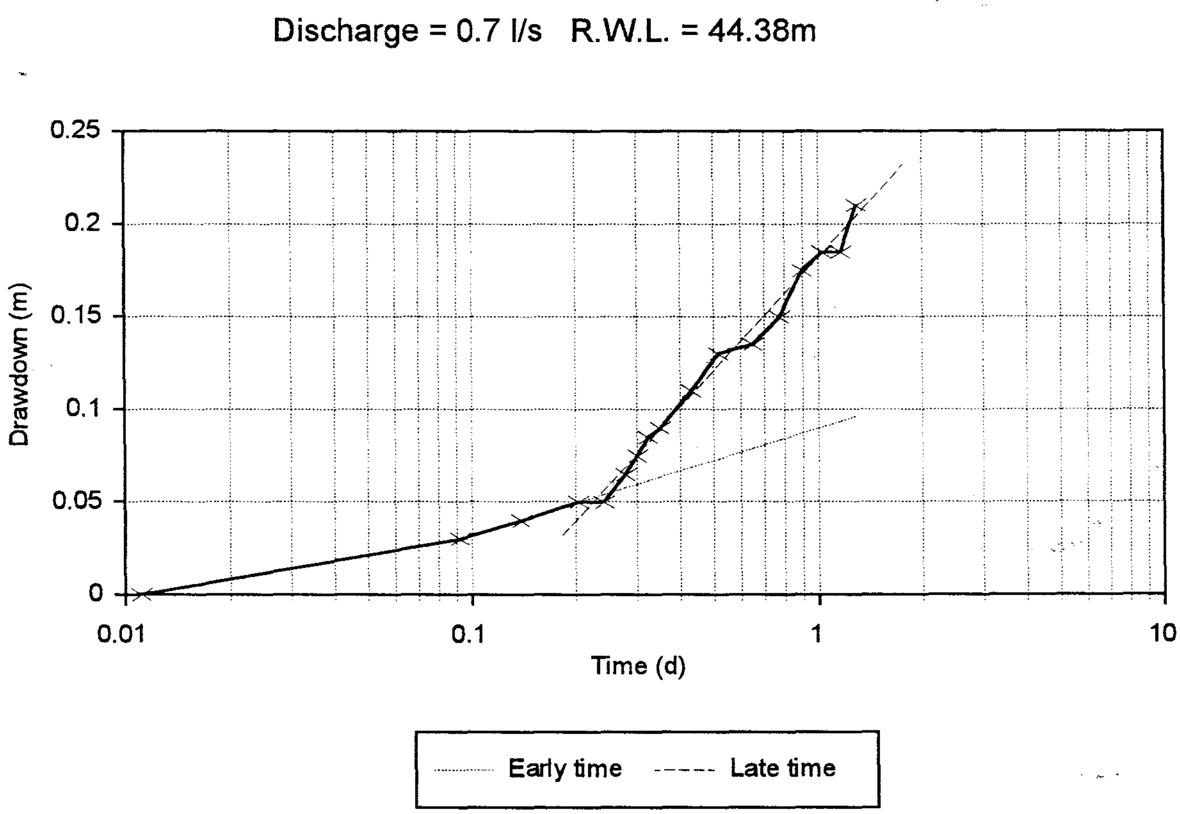
Discussion

Although insufficient early-time drawdown data was collected and a higher discharge rate should have been used for the test, an early- and a late-time segment of the curve can be identified (Figure 7.8). The recovery test data was unavailable. The borehole was first tested using the maximum drawdown method, and a yield of about 200 m^3/day was recommended. The farmer's initial production yield was in the region of 85 - 100 m^3/day, but the borehole failed and the yield was reduced dramatically to about 5 m^3/day.

The late-T method could not be used because the depth of the main water strike is not known. The drawdown-to-boundary and distance-to-boundary methods indicate that the production yield should be about 6 - 7 m^3/day, which correlates well with the existing pumping rate. In this example the upper production yield could be defined by the recharge method which may be reliable because of the small catchment area.

The storage method could not be used because the thickness of the aquifer is unknown. In this small, but transmissive aquifer, the yield obtained using the throughflow method is unrealistic because the aquifer receives insufficient recharge to supply what it can theoretically transmit.

Figure 7.8 Borehole BRG 7: Constant discharge test



Borehole DEW A1

Location:	Dewetsdorp, Orange Free State, South Africa.
Lithology:	Balfour Formation, Beaufort Group, Karoo Sequence.
Geological log:	Unavailable. The Balfour Formation consists of interbedded sandstones and mudstones.
Depth:	23.3 m
Water strikes:	Unknown.
Final blow yield:	Unknown.
Current Use:	Production borehole for Dewetsdorp municipality.

Aquifer properties

T-early (m^2/d):	10
T-late (m^2/d):	10
T-recovery (m^2/d):	11
S_f:	0.0012
S_m:	0.004
t/t' intercept:	2.8
RWL-main water strike (m):	-
Dist.-boundary (m):	10
Time-boundary (d):	-
∆h (m):	-
Catchment area (km^2):	13
Recharge (mm/a):	12.8*[1]
Abstractable % of recharge:	11
Aquifer thickness (m):	20
B/h success rate (%):	70
Years without recharge:	3
Aquifer width (m):	2 000
Hydraulic gradient:	0.017

*[1] Kirchner, et al, 1991

Borehole yield (m^3/d)

Recovery method:	75
Late-T method:	-
Drawdown-boundary:	61
Distance-boundary:	-

Aquifer yield (m^3/d)

Recharge:	50
Storage:	73
Throughflow:	37

Current yield (m^3/d): 35

Failed at (m^3/d): -

Discussion

This drawdown curve indicates that leakage occurred after four days of pumping (Figure 7.9). The borehole yield assessment methods indicate that the production yield could be increased to about 60 - 75 m^3/day, whereas the recharge and throughflow methods caution against abstracting more than about 40 - 50 m^3/day. Because the drawdown curve resembles a classical Theis curve without boundaries or dual porosity effects, neither the distance-to-boundary method nor the late-T methods could be used.

This is a good example for the application of the recharge and throughflow methods, because the catchment area is relatively small, the borehole is shallow, the hydraulic gradient is known and the seepage face is well defined. The production yield of this borehole could probably be increased to 60 m^3/day. With regular monitoring it would be possible to established whether the yield could be further increased to about 75 m^3/day or if it would need to be reduced to about 40 m^3/day.

Figure 7.9 Borehole DEW 1A: Constant discharge test

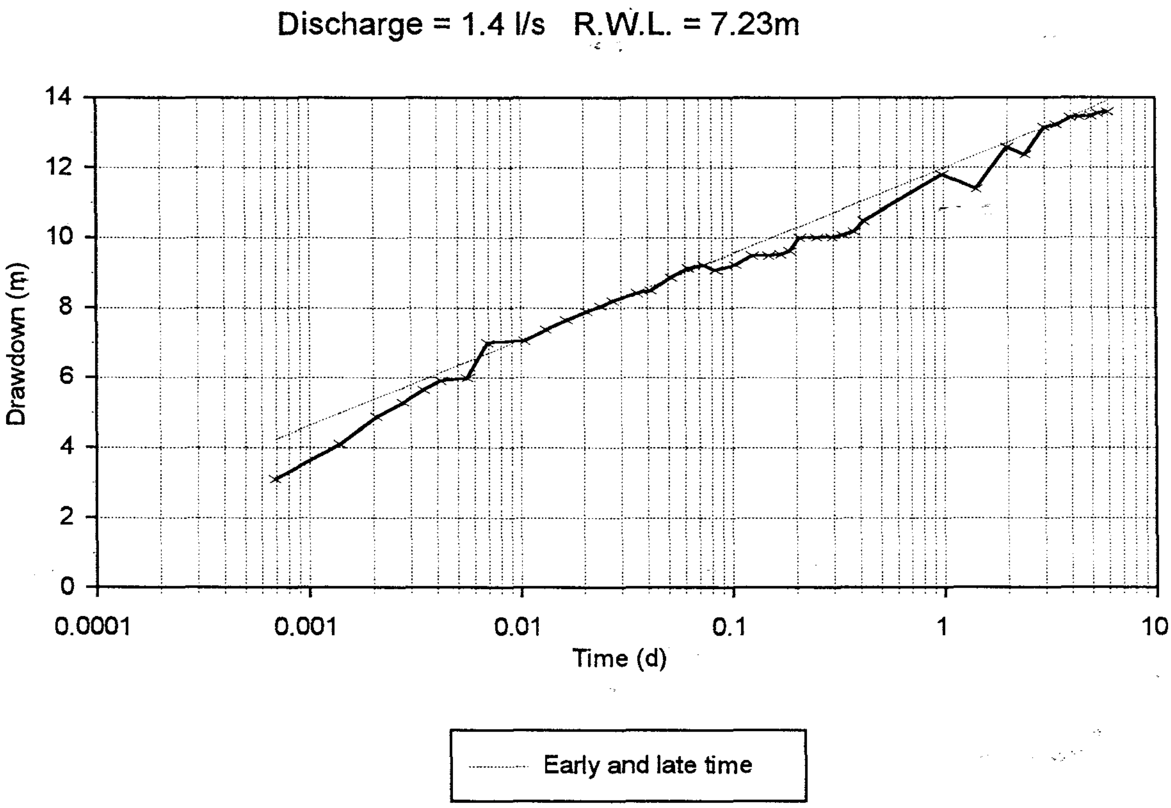
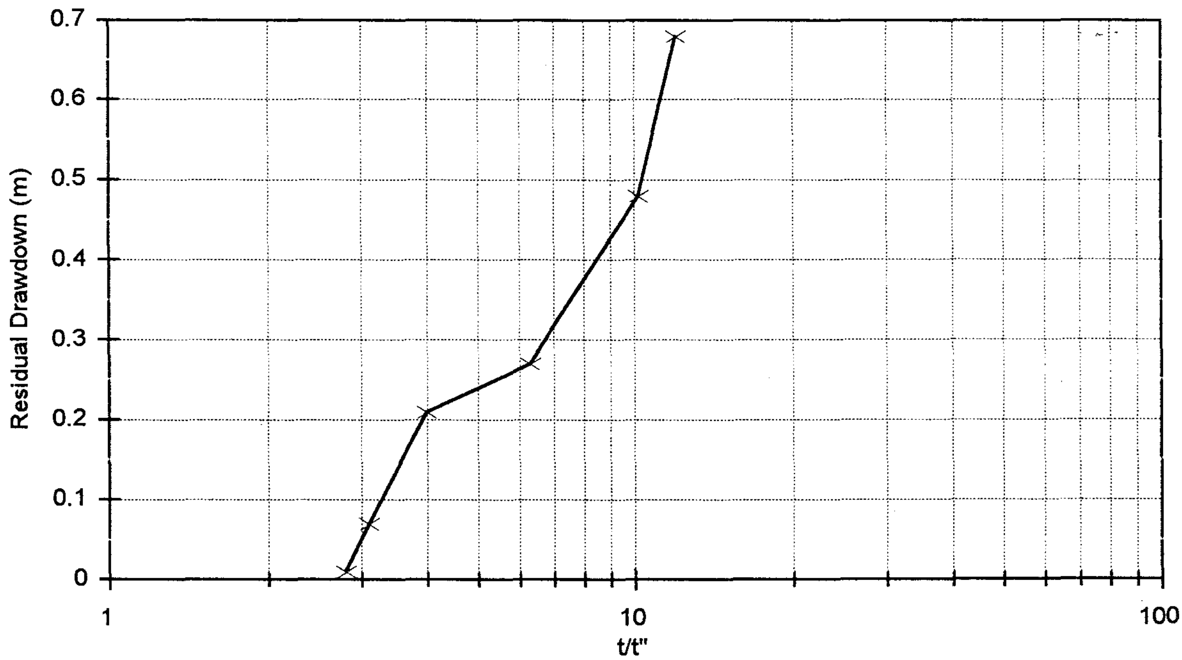


Figure 7.10 Borehole DEW 1A: Recovery test



7.3 CAPE SUPERGROUP AQUIFERS

The three boreholes assessed in this section are used by the municipalities of Dysseldorp and Calitzdorp in the southern Cape, near Oudtshoorn. Two of the boreholes (VR 11 and DL 15) are located in the upper section of different wellfields where the influence of other production boreholes is believed to be least. The information was obtained from a draft report by the Department of Water Affairs and Forestry:

J.C. Kotze, 1995. Interim report on the performance of the Little Karoo rural water supply scheme. DWAF Report No. GH 3858.

Borehole VR 11

Location:	Dysselsdorp, Western Cape Province, South Africa.	
Lithology:	Peninsular Formation, Table Mountain Group, Cape Supergroup.	
Geological log:	0 - 4 m	Clay soil with quartzite boulders
	5 - 15 m	Weathered sandstone
	15 - 224 m	Quartzite, fractured in places
Depth:	224 m	
Water strikes:	139 m - 2 l/s; 183 - 194 m - 8 l/s; 200 - 210 m - 10 l/s	
Final blow yield:	20 l/s	
Current use:	Municipal production borehole.	

Aquifer properties

T-early (m^2/d):	103
T-late (m^2/d):	18
T-recovery (m^2/d):	18
S_f:	0.00002
S_m:	0.00056
t/t' intercept:	< 1
RWL-main water strike (m):	75
Dist.-boundary (m):	12
Time-boundary (d):	1.5
Δh (m):	0.8*1
Catchment area (km^2):	12*2
Recharge (mm/a):	20*2
Abstractable % of recharge:	83
Aquifer thickness (m):	-
Aquifer width (m):	200
Hydraulic gradient:	0.025

*1 Drawdown difference between the last two readings.

*2 Kotze, 1995

Borehole yield (m^3/d)

Recovery method:	0
Late-T method:	813
Drawdown-boundary:	599
Distance-boundary:	480

Aquifer yield (m^3/d)

Recharge:	546
Storage:	-
Throughflow:	75

Current yield (m^3/d): 419 - 457

Failed at (m^3/d): -

Discussion

This borehole forms part of a wellfield and has been chosen for analysis because it is the uppermost borehole in the wellfield, and the nearest production borehole is about 400 m down gradient from it. If this pump test had been extended beyond three days, it is quite likely that the drawdown curve would have continued with its late steep gradient and thus shown clearer signs of boundary effects (Figure 7.11).

Borehole water level, abstraction and rainfall data have been monitored for twenty five months (Figure 7.13). The water level data was usually taken eight hours after the pump had been switched off and represents in certain cases the residual drawdown measurement rather than the borehole's dynamic rest water level. The rainfall data was obtained from a gauge about 3 km from the borehole (Figure 7.14).

The water level reading for month 19 has been disregarded, as this reading was either incorrectly taken or the water level in the borehole was still recovering. The borehole's elevation is 812.2 m.a.m.s.l. and the water level of month 19 is given as 618.29 m.a.m.s.l., giving a water level reading of 193.91 m.b.g.l. This level, according to the geological log lies within a major water strike zone. It is unlikely that the water level lies within this zone eight hours after pump shut-down.

The borehole yielded on average 457 m^3/day during months 9 - 11. During this period the average rainfall was 110 mm/month and there was a general rise in the borehole's water level. During months 18 - 23, the borehole yielded an average of 419 m^3/day, the average rainfall was 47 mm/month and the water level in the borehole declined. From this information, and given that the production borehole 400 m from this borehole could have an influence on this borehole, it can be assumed that without other production boreholes in the wellfield, this borehole could probably sustain a production yield in excess of 400 m^3/day.

The 813 m^3/day obtained from the late-T method appears to be too high, however, if the first major water strike at 183 m was used in obtaining the available drawdown value (s in eq.6.10), a more acceptable yield of 628 m^3/day would have been obtained. This is similar to the 599 m^3 /day obtained using the drawdown-to-boundary method, and could possibly be viewed as the upper long-term abstraction rate. The late-time transmissivity value was accepted as a reasonable value even though insufficient late-time data during the constant rate test was gathered. The reason for accepting this value was because the transmissivity value obtained from the recovery curve (Figure 7.12) matched the late-time value obtained from the drawdown curve. The distance-to-boundary method, although difficult to apply because of the problem of assigning a Δh value, probably predicts the lower production rate. The sensitivity of the yield (Q) in the distance-to-boundary method to the Δh value is high. If a Δh value of 1 m as opposed to 0.8 m was used, a discharge of 600 m^3/day would have been obtained.

The recharge method should not be applied to cases where deep water strikes are encountered because of the problems associated with estimating the recharge area and the width of the seepage face. In this example, the recharge method gives a fairly accurate estimate of the borehole's potential - possibly because the recharge area was carefully determined in a detailed hydrogeological study (Kotze, 1995) and because the seepage face at the aquifer's outlet, like the valley bottom in which the borehole is located, is narrow. It is difficult to determine the aquifer's thickness and therefore the storage method was not applied.

The throughflow method should be applied with reservations in cases where deep water strikes are encountered, because it may be unreasonable to assume that the valley width represents the full seepage face. Assuming the 200 m seepage face is reasonable in this case, the throughflow method shows that the early transmissivity value is more representative of the aquifer at the seepage face than the late transmissivity value. If the early transmissivity value is applied to the throughflow method a discharge of 427 m^3/day is obtained, which is far more realistic than the 75 m^3/day obtained using the late-time transmissivity value.

Figure 7.11 Borehole VR 11: Constant discharge test

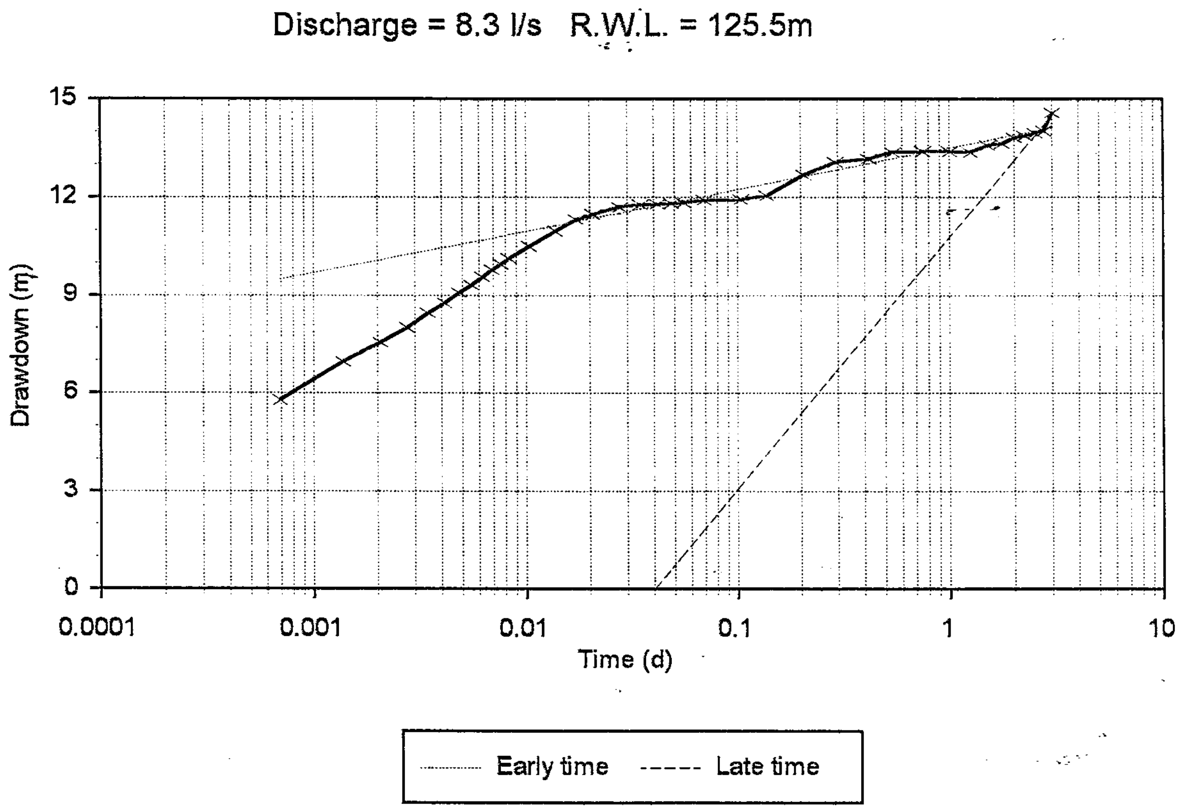


Figure 7.12 Borehole VR 11: Recovery test

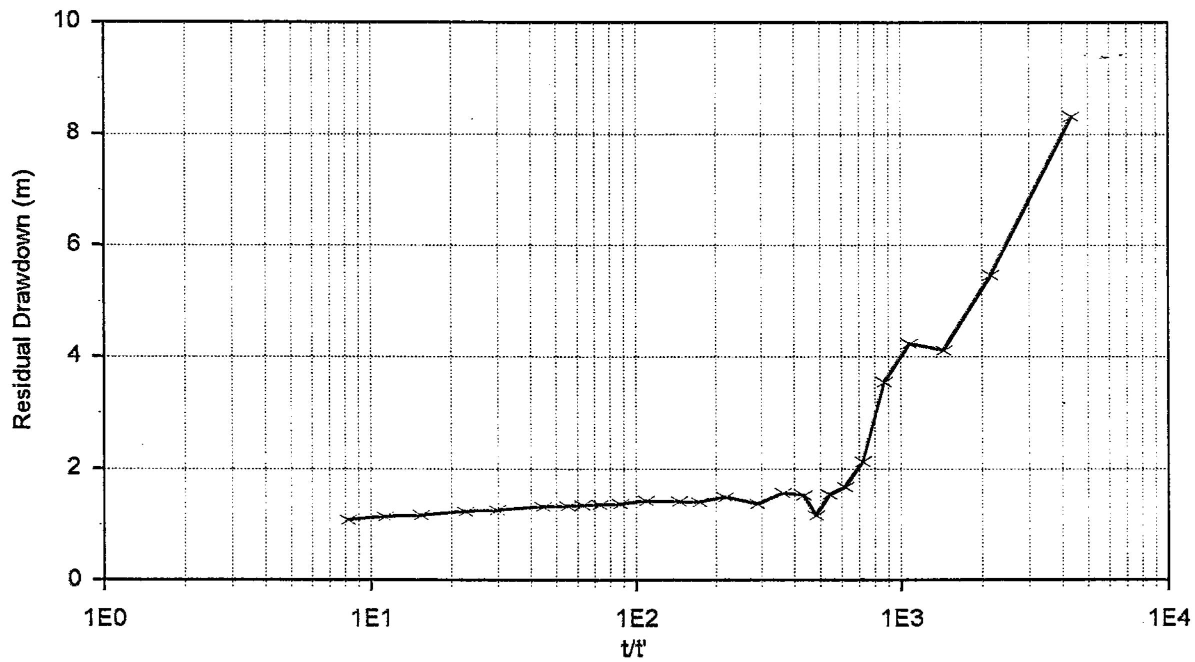


Figure 7.13 Borehole VR 11: Abstraction and water level data

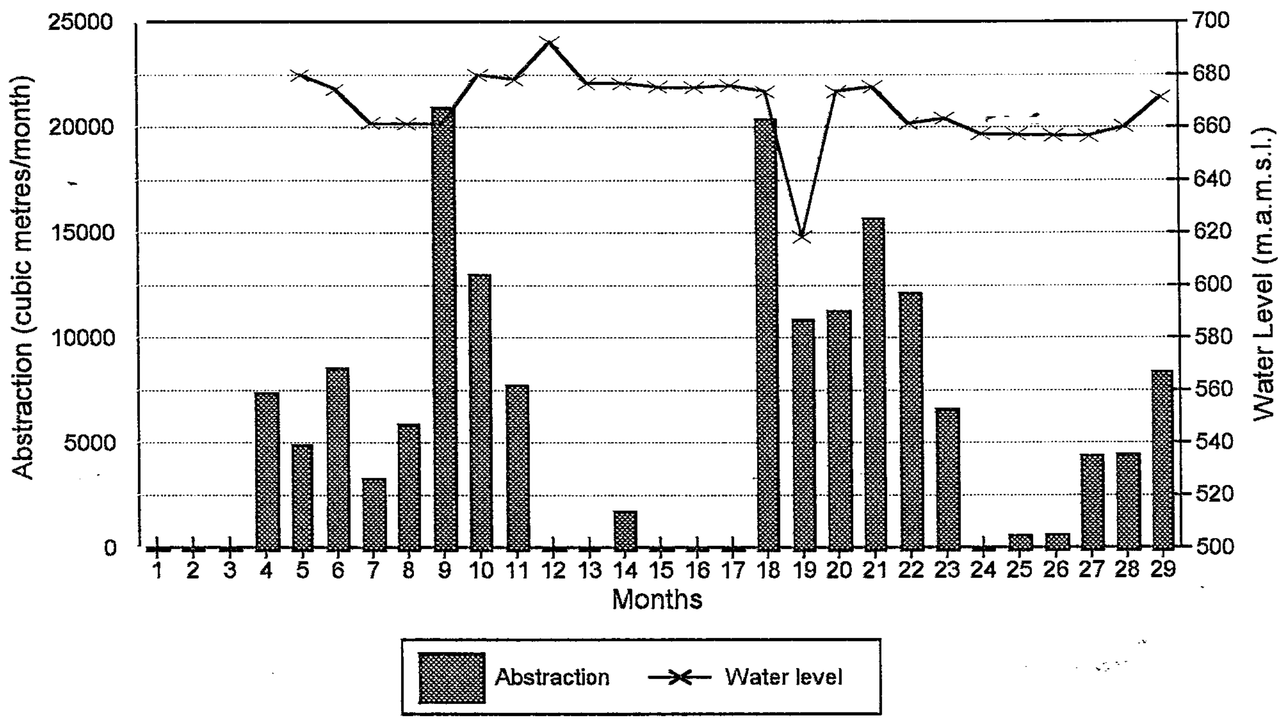
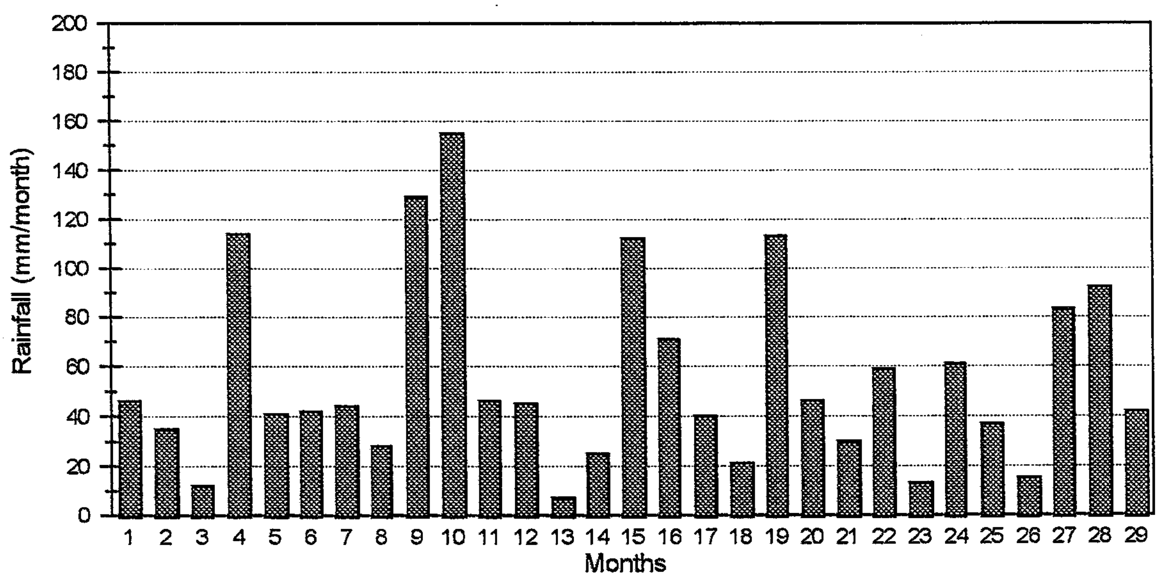


Figure 7.14 Rainfall taken at Wildebeestvlakte rain gauge



Borehole VG 3

Location:	Dysselsdorp, Western Cape Province, South Africa.	
Lithology:	Baviaanskloof Formation, Table Mountain Group, Cape Supergroup.	
Geological log:	0 - 13 m	Alluvium (cased off)
	13 - 110 m	Sandstone (perforated casing from 96 m)
	110 - 207 m	Quartzite
Depth:	207 m	
Water strikes:	110 m - 6 l/s; 174 m - 3 l/s; 190 m to 196 m - 3 l/s	
Final blow yield:	12 l/s	
Current use:	Municipal production borehole.	

Aquifer properties		**Borehole yield (m^3/d)**	
T-early (m^2/d):	9	Recovery method:	507
T-late (m^2/d):	-	Late-T method:	-
T-recovery (m^2/d):	4	Drawdown-boundary:	204
S_f:	0.00002	Distance-boundary:	242
S_m:	0.00056		
t/t' intercept:	3		
RWL-main water strike (m):	104	**Aquifer yield (m^3/d)**	
Dist.-boundary (m):	44		
Time-boundary (d):	2	Recharge:	384
Δh (m):	4*1	Storage:	-
Catchment area (km^2):	9*2	Throughflow:	35
Recharge (mm/a):	20*2		
Abstractable % of recharge:	78		
Aquifer thickness (m):	-	**Current yield (m^3/d):**	**206**
Aquifer width (m):	200		
Hydraulic gradient:	0.025	**Failed at (m^3/d):**	-

*1 Drawdown 'jump' after two days of pumping.

*2 Kotze, 1995

Discussion

The flattening of the drawdown curve during much of the constant discharge test (Figures 7.15) and the rapid initial recovery (Figures 7.16) are indicative of leakage, which is likely to have come from the 7 m of saturated alluvium and the sandstones. The late time curve (between days two and three, Figure 7.15) does not reveal boundary or double porosity effects. This curve could still be affected by leakage and therefore the slightly higher transmissivity value that would be obtained from this portion of the drawdown curve is likely to be unrealistic.

This borehole lies approximately 8 km downstream from borehole VR 11 and similar abstraction and water level data has been monitored (Figure 7.17). Within 300 m of VG 3 is a borehole which is used intermittently, and thus may have an effect on the water level readings of VG 3. This could well have been the case in months 7 and 8, where both the groundwater abstraction and the recorded water levels were relatively low. The period up to pump failure in month 19 gives an average yield of 206 m^3/day with an average rainfall of 56.3 mm/month (Figure 7.18). The water level in the borehole was relatively stable, indicating that this could be considered a safe production yield.

Months 21 - 25 probably indicate slight over abstraction from the borehole. The average monthly abstraction during this period was 256 m^3/d and the rainfall 40 mm/month. The water level during this period dropped nearly 10 m below the trend it was following up to month 18.

The recovery method predicts a discharge rate that is more than double what this borehole can supply. The rapid recovery is likely to be a result of leakage from the overlying alluvium and sandstones, and should be treated with caution when predicting long-term production yields. The late-T method was developed for fractured aquifers which display early- and late-time drawdown curves, and therefore could not be applied to this borehole. The drawdown-to-boundary method accurately predicts a suitable production yield. The distance-to-boundary method should not be applied in this case because of the difficulty in obtaining a suitable Δh value. If the 4 m drawdown 'jump' after two days of pumping is taken as the Δh value, a slightly high yield of 242 m^3/day is obtained.

The recharge method is likely to be unreliable. Where deep water strikes are encountered, it is difficult to define the area contributing to recharge and the width of the seepage face.

In order for an aquifer with an average transmissivity value of 10 m^2/day and a high hydraulic gradient of 0.025 to allow 200 m^3/day to flow through it, it would require a seepage face of 800 m. Although this may be the case, it may also be that the principles on which the throughflow method is based, do not hold in this particular example.

Figure 7.15 Borehole VG 3: Constant discharge test

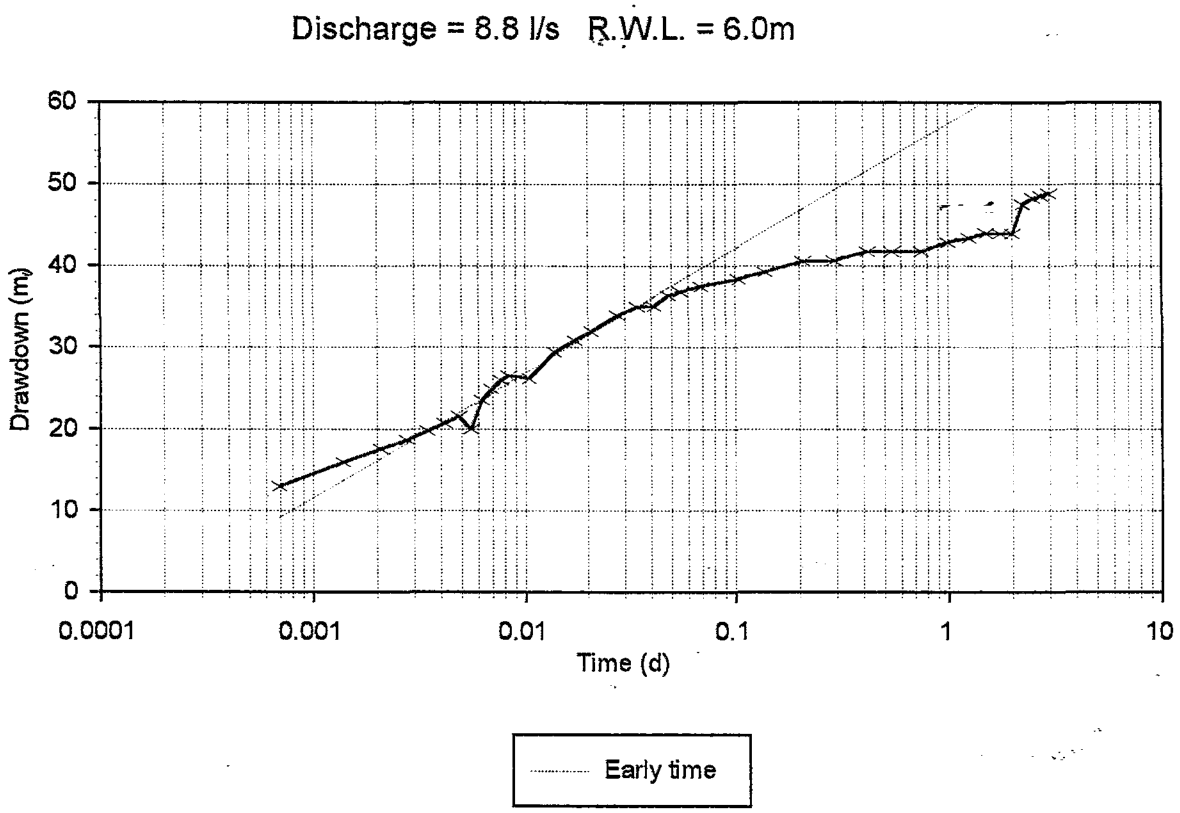


Figure 7.16 Borehole VG 3: Recovery test

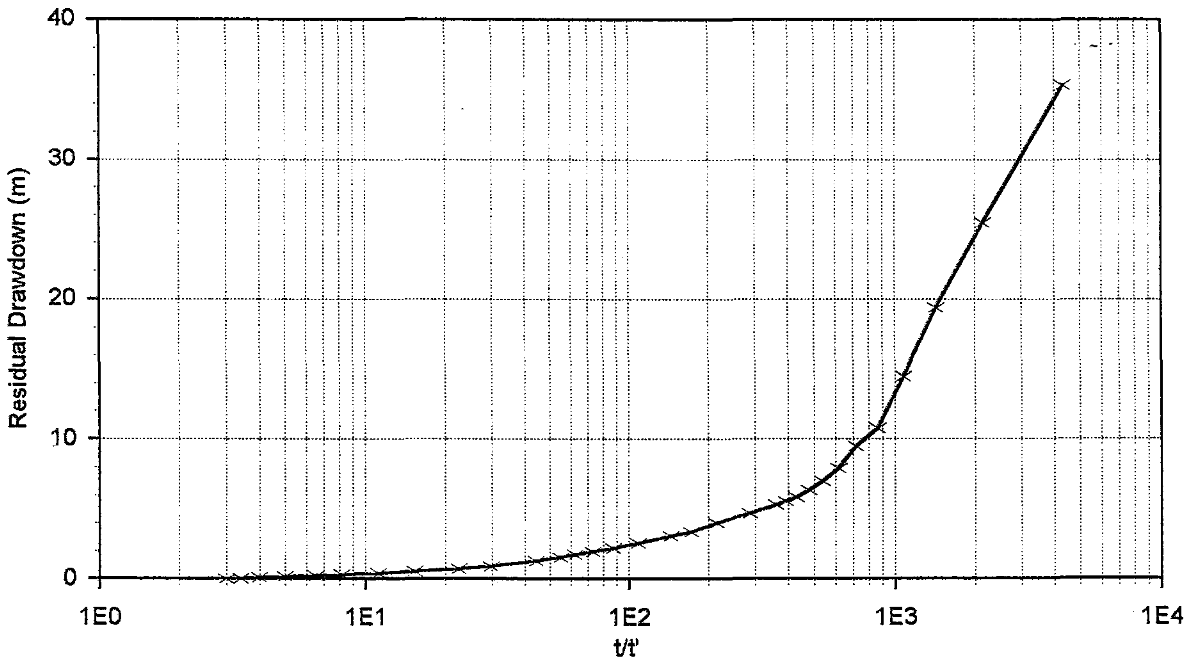


Figure 7.17 Borehole VG 3: Abstraction and water level data

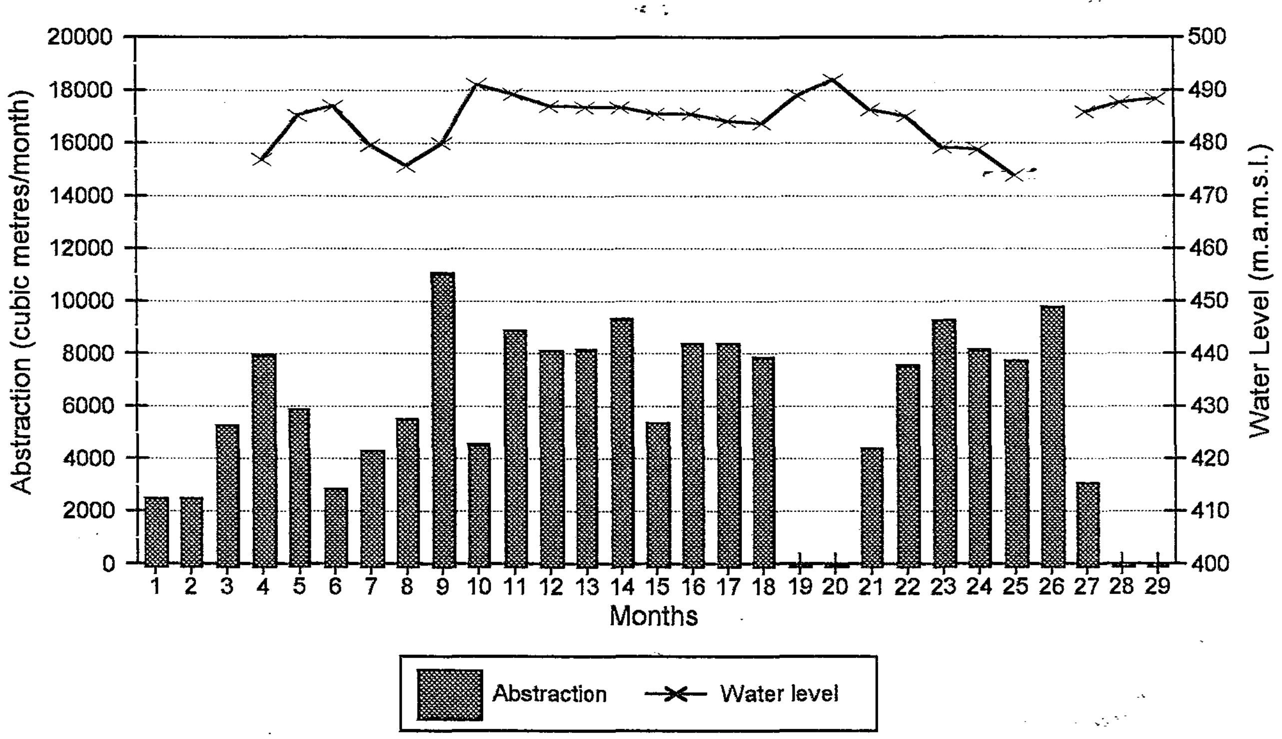
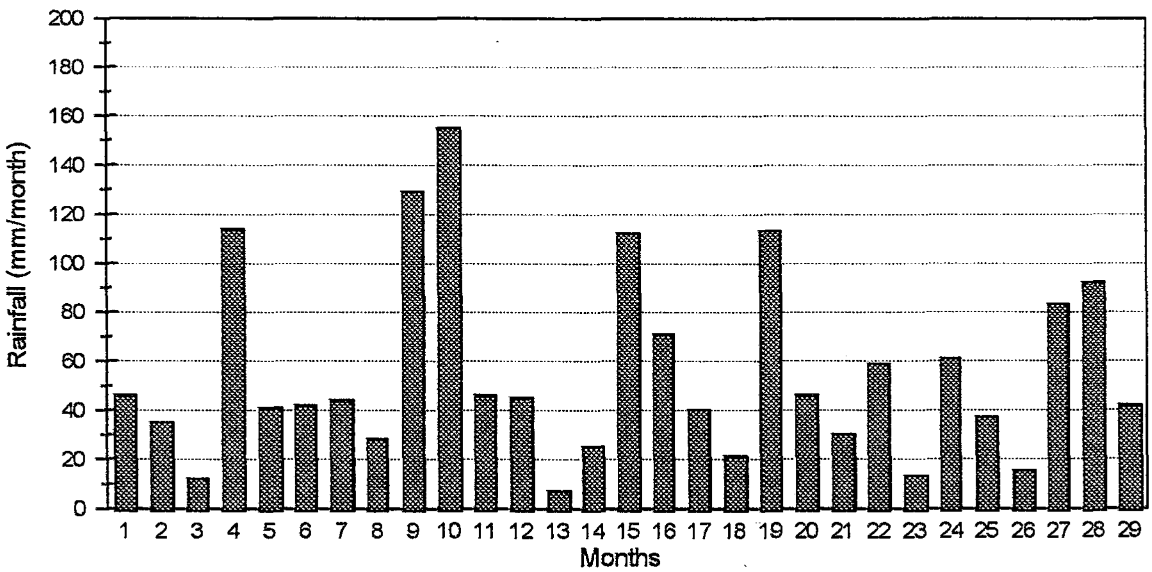


Figure 7.18 Rainfall taken at Wildebeestvlakte rain gauge



Borehole DL 15

Location:	Calitzdorp, Western Cape Province, South Africa.	
Lithology:	Baviaanskloof Formation, Table Mountain Group, Cape Supergroup.	
Geological log:	0 - 5 m	Alluvium and weathered sandstone.
	5 - 137 m	Quartzite.
Depth:	137 m	
Water strikes:	135 m - 30 l/s	
Final blow yield:	33 l/s	
Current use:	Municipal production borehole.	

Aquifer properties

T-early (m^2/d):	27
T-late (m^2/d):	7
T-recovery (m^2/d):	7
S_f (estimate):	0.0001
S_m (estimate):	0.001
t/t' intercept:	0.4
RWL-main water strike (m):	128
Dist.-boundary (m):	25
Time-boundary (d):	0.3
Δh (m):	8
Catchment area (km^2):	7*[1]
Recharge (mm/a):	20*[1]
Abstractable % of recharge:	49
Aquifer thickness (m):	-
Aquifer width (m):	300
Hydraulic gradient:	0.016

*[1] Kotze, 1995

Borehole yield (m^3/d)

Recovery method:	0
Late-T method:	512
Drawdown-boundary:	364
Distance-boundary:	383

Aquifer yield (m^3/d)

Recharge:	188
Storage:	-
Throughflow (early-T):	64

Current yield (m^3/d): 66

Failed at (m^3/d): -

Discussion

This borehole is situated in the upper parts of a wellfield, and like the other boreholes in the wellfield, it was sited on a fault zone. The drawdown curve (Figure 7.19) indicates that either fractures were dewatered during the test, or that a barrier boundary was encountered (Figure 6.4). The former option is the most likely because fracturing is commonly associated with faults, and the high blow yield of 33 l/s indicated the presence of secondary openings. The water level data shows that the current production yield of 66 m^3/day is well tolerated and that it could be increased (Figure 7.21), although further monitoring would be necessary to establish the maximum production yield.

The high yield obtained using the late-T method is a result of the deep water strike, and thus should be treated with caution. The drawdown-to-boundary method may give an indication of the borehole's yield potential, however this could only be established through a monitoring programme where the borehole is pumped at ± 360 m³/day. A close inspection of the drawdown curve shows that an early-time T-value could have been obtained from the straight line segment between 0.02 - 0.1 days. The T-value obtained from this slope is 39 m²/day, and the s-value is 16 m, giving a yield of 331 m³/day using the drawdown-to-boundary method - a yield which is similar to the first drawdown-to-boundary method's yield of 364 m³/day. The distance-to-boundary method gives a similar yield to the drawdown-to-boundary method, but a unique Δh is difficult to establish.

The recharge method gives an acceptable yield, however the deep water strike makes this method unreliable because of the difficulties associated with determining the recharge area. The storage method was not used because it was not possible to determine the aquifer's thickness. While the throughflow method gives an acceptable yield when the higher transmissivity value is used, it should not be considered to be reliable because the assumption that the valley width is the same as the seepage face may not be correct.

Figure 7.19 Borehole DL 15: Constant discharge test

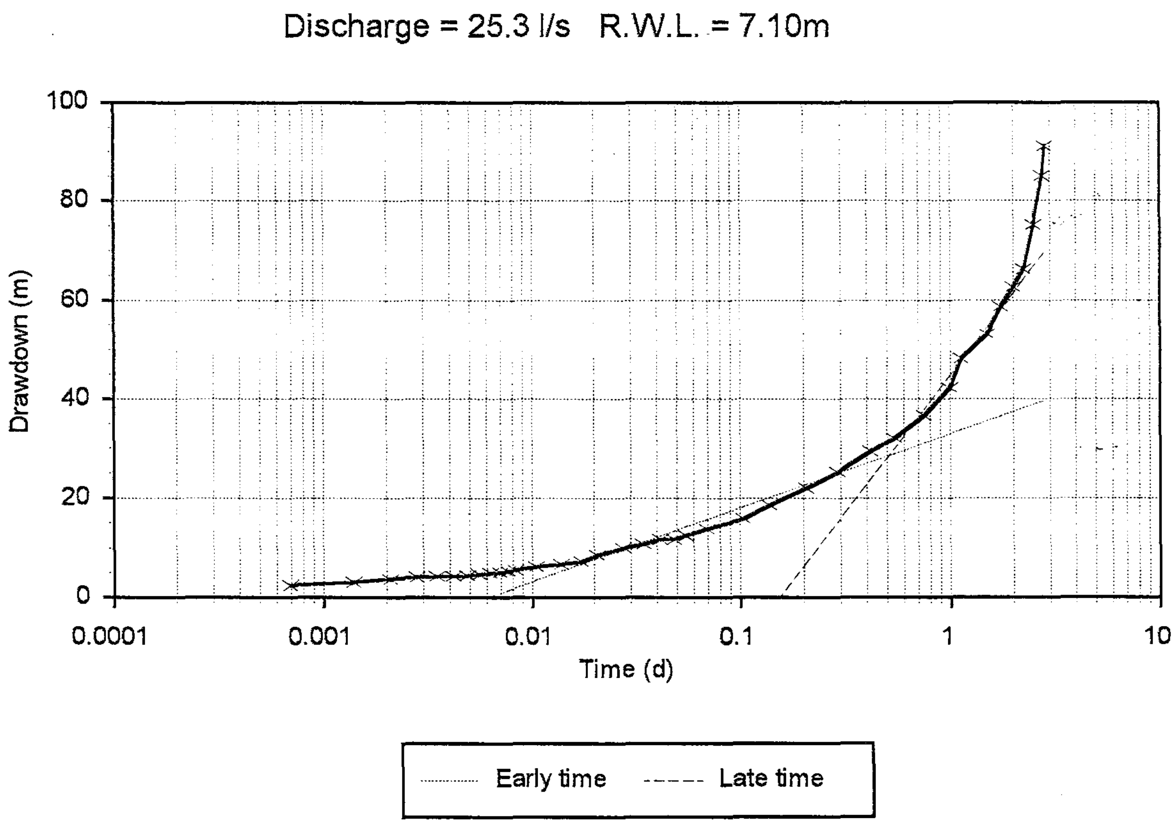


Figure 7.20 Borehole DL 15: Recovery test

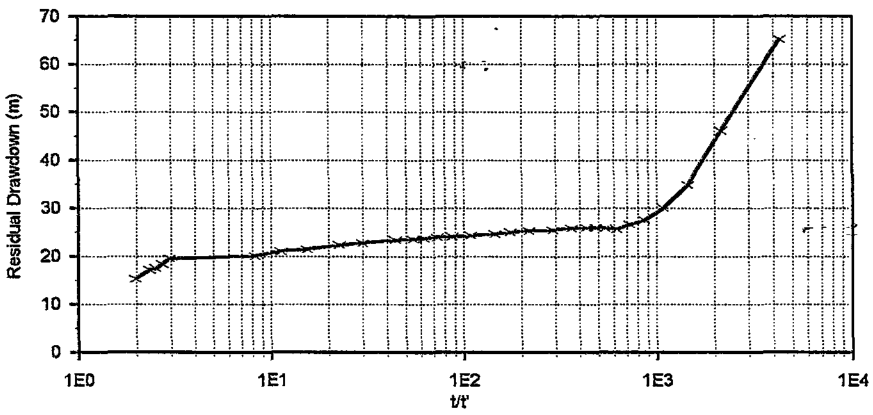


Figure 7.21 Borehole DL 15: Abstraction and water level data

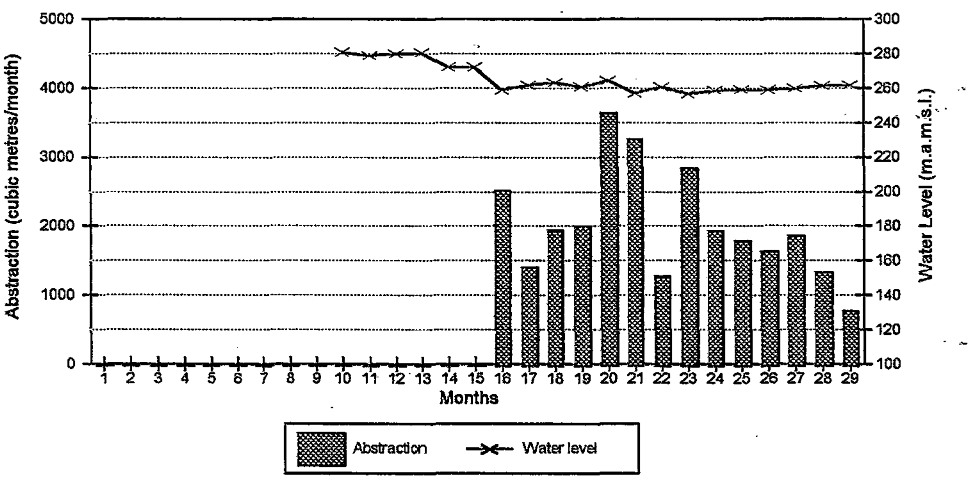
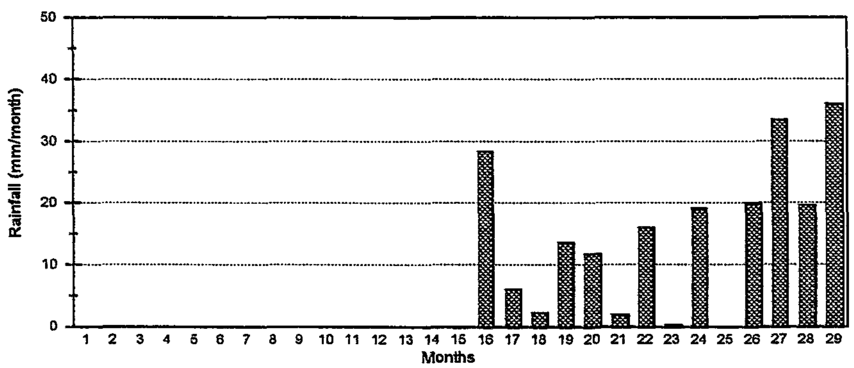


Figure 7.22 Borehole DL 15: Rainfall data from the Calitzdorp water treatment works



7.4 NAMAQUALAND METAMORPHIC COMPLEX AND GARIEP COMPLEX AQUIFERS

The boreholes used in this section are located in the dry north-western corner of South Africa, near Springbok. The information was supplied by PD Toens and Associates.

Borehole KG 108

Location:	Kommadaggasdorp, Northern Cape, South Africa	
Lithology:	Khurisberg Subgroup, Okiep Group, Namaqualand Metamorphic Complex.	
Geological log:	0 - 3 m	Scree.
Depth:	3 - 33 m	Weathered schist.
	33 - 109 m	Schist, fractured at 38 m, 41 m, 48 m and 64 m.
	109 - 118 m	Quartzite.
	118 - 139 m	Schist, fractured at 122 m.
Water strikes:	38 m, 41 m, 48 m, 64 m, 122 m.	
Final blow yield:	7 l/s	
Current use:	Production borehole.	

Aquifer properties

T-early (m^2/d):	3.4
T-late (m^2/d):	-
T-recovery (m^2/d):	17.5
S_f (estimate):	0.0001
S_m (estimate):	0.001*1
t/t' intercept:	0.8
RWL-main water strike (m):	-
Dist.-boundary (m):	33
Time-boundary (d):	1.8
Δh (m):	7
Catchment area (km^2):	-
Recharge estimate (mm/a):	1*2
Abstractable % of recharge:	-
Aquifer thickness (m):	22
B/h success rate (%):	70
Aquifer width (m):	400
Hydraulic gradient:	0.02

*1 this value is likely to be conservative
*2 1.5% of MAP (MAP = ±70 mm/a)
*3 assuming 100% groundwater abstraction

Borehole yield (m^3/d)

Recovery method:	0
Late-T method:	-
Drawdown-boundary:	64
Distance-boundary:	99

Aquifer yield (m^3/d)

Recharge:	-
Storage:	-
Throughflow:	27*3

Current yield (m^3/d): 55

Failed at (m^3/d): -

Discussion

The drawdown curve of this borehole shows signs of leakage from the weathered schists after about one hour of pumping (Figure 7.23). The abstraction data shows that over the thirteen months of regular use with an average yield of 55 m^3/day, the water level in the borehole dropped 7.4 m (Figure 7.25). During the last five months the abstraction rate decreased on average to 45 m^3/day and the water level in the borehole stayed fairly level. A major rainfall event also occurred during this period (Figure 7.26). While a production yield of 45 m^3/day seems fairly safe, 55 m^3/day seems slightly high, although this would need to be verified with further monitoring.

The recovery test shows incomplete recovery six days after the constant rate test was stopped (Figure 7.24). This provides a warning that a conservative production yield should be recommended.

The late-T method cannot be used because low-permeability boundary effects are not shown in the drawdown curve. The late-time segment of the drawdown curve between days two and three appears to be effected by leakage from the weathered schists, and therefore does not represent flow from the matrix to the fractures in the dual porosity model.

If the 33 m inflection point on the drawdown curve is used as the s-value in the drawdown-to-boundary method, a yield of 64 m^3/day is obtained. In order to be more conservative (due to incomplete recovery), the s-value could be taken as the thickness of the saturated weathered zone, which is 22 m. This gives a more reasonable long term yield of 42 m^3/day.

The distance-to-boundary method is difficult to apply because the effect of leakage on the drawdown curve makes the determination of Δh problematic. A Δh value of 7 m is obtained if the distance between the 33 m inflection point and the start of the late-time segment of the drawdown curve at day two is used. This gives a yield of 99 m^3/day which appears to be higher than the sustainable yield of the borehole.

The yield obtained using the throughflow method should not considered realistic, because large errors could have been made in the estimation of seepage face and hydraulic gradient. The storage and recharge methods could not be used due to problems associated with defining the size of the aquifer and the area contributing to recharge.

Figure 7.23 Borehole KG 108: Constant discharge test

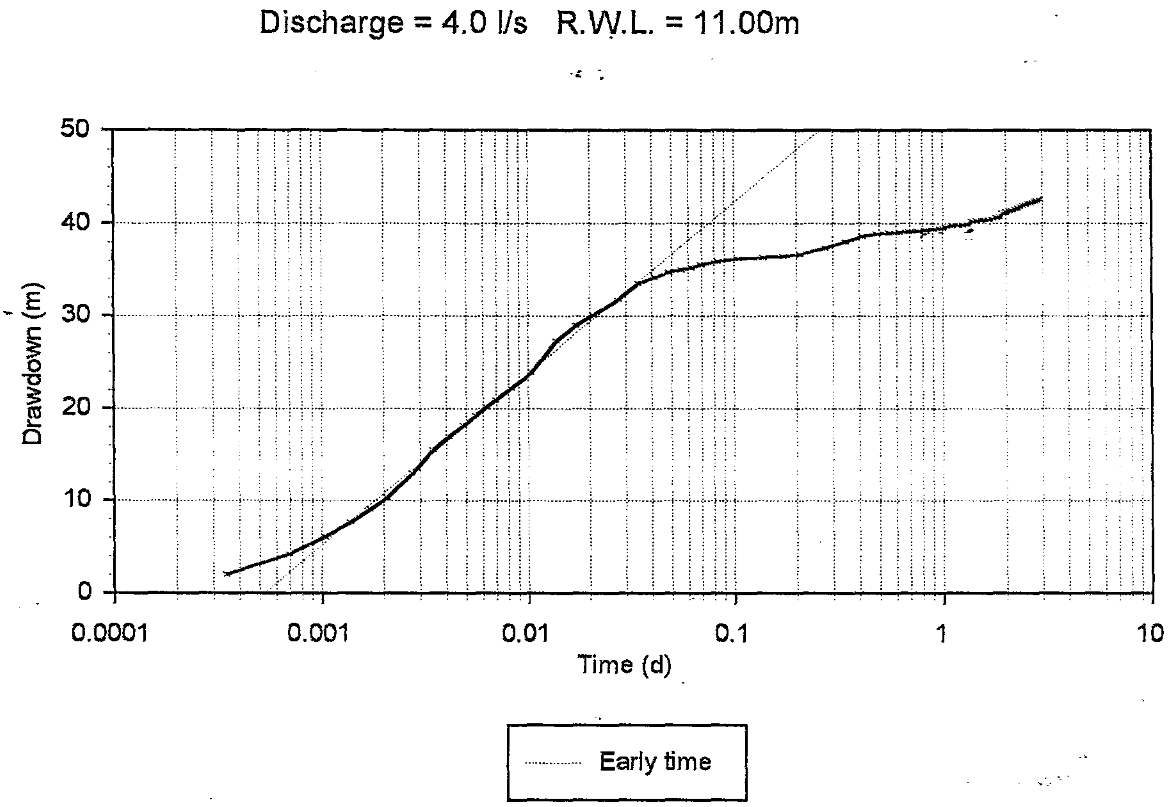


Figure 7.24 Borehole KG 108: Recovery test

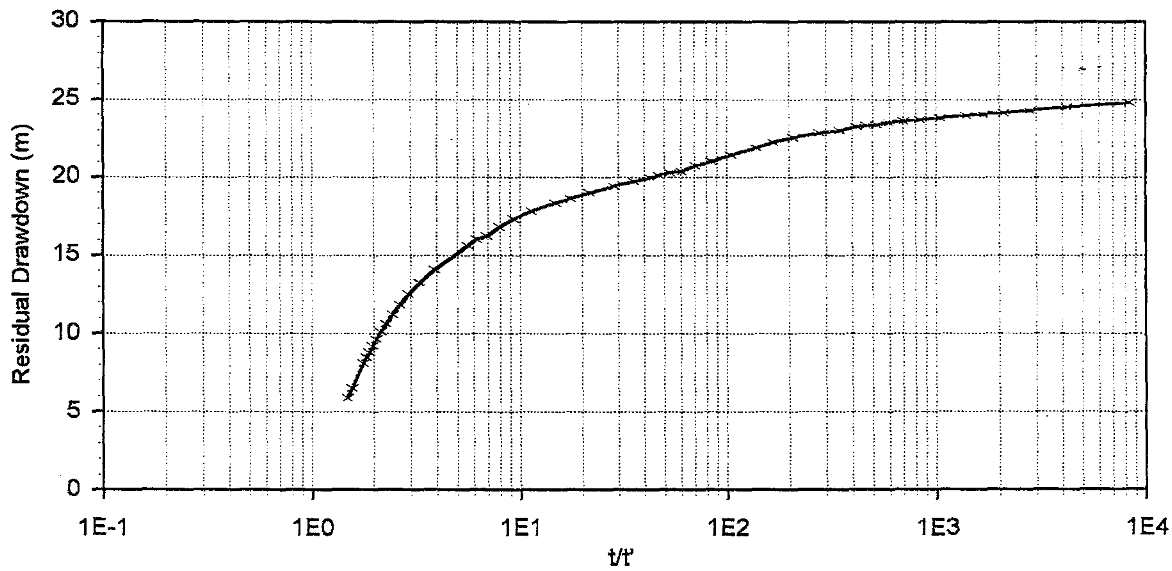


Figure 7.25 Borehole KG 108: Abstraction and water level data

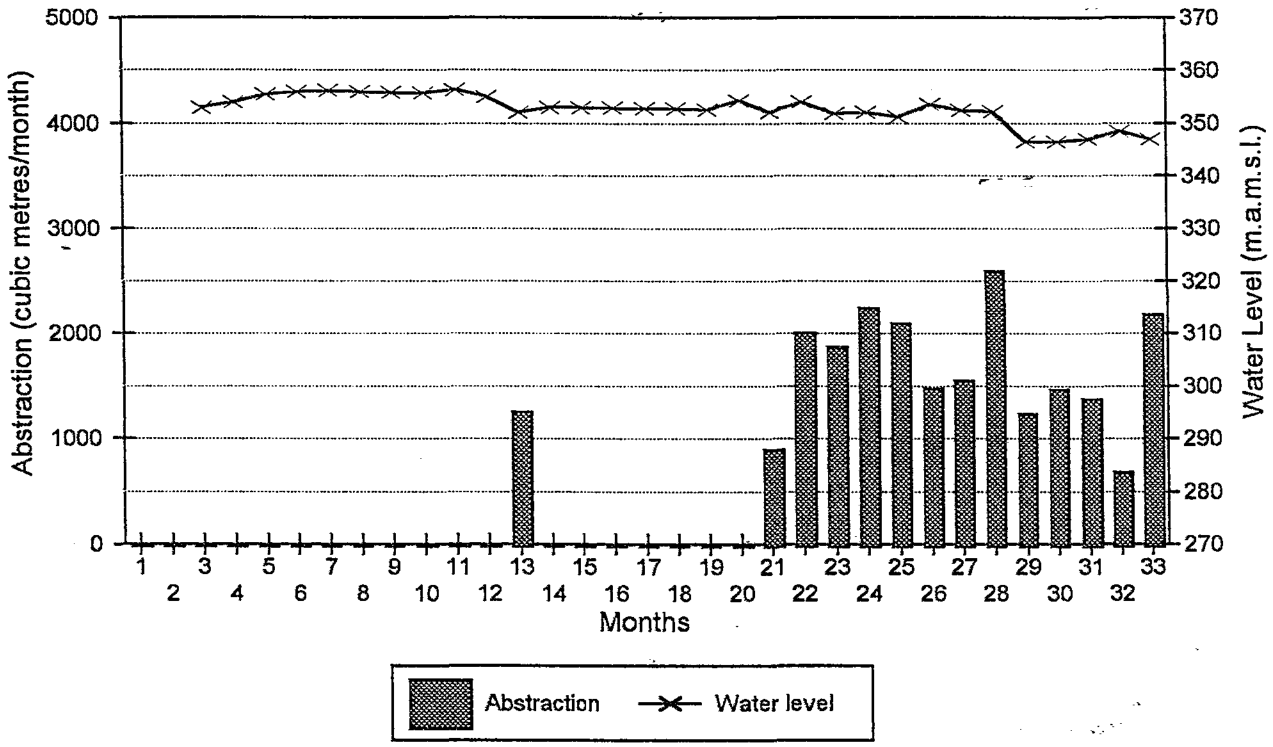
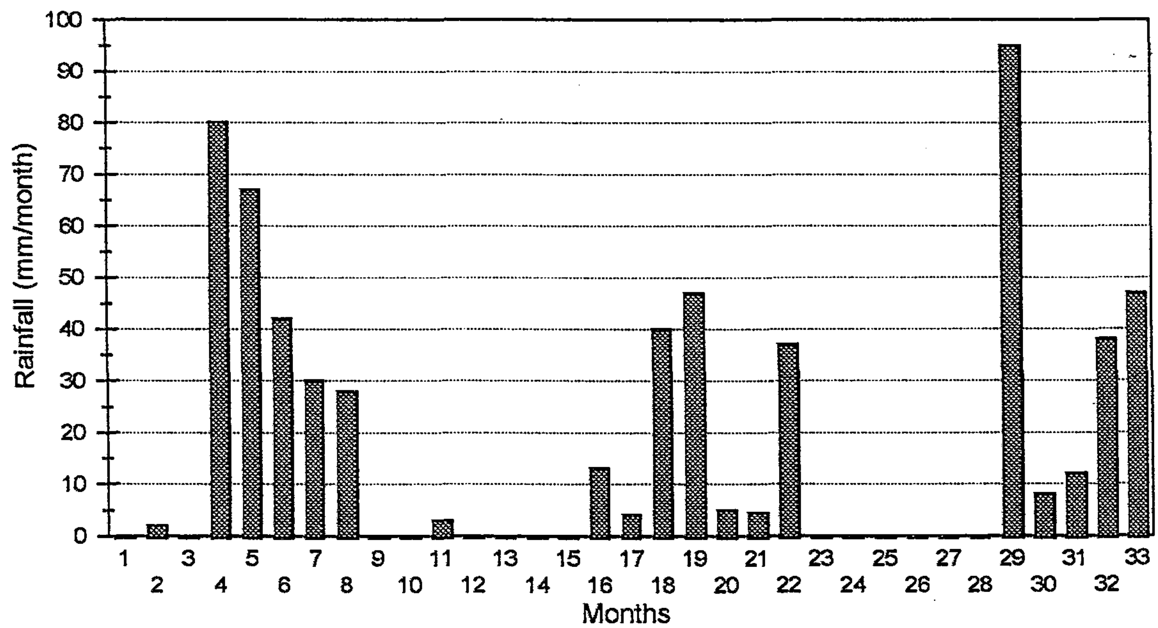


Figure 7.26 Borehole KG 108: Rainfall data



Borehole KG 109

Location:	Kommadaggasdorp, Northern Cape, South Africa	
Lithology:	Khurisberg Subgroup, Okiep Group, Namaqualand Metamorphic Complex.	
Geological log:	0 - 3 m	Alluvium.
	3 - 74 m	Weathered schist, fractured at 53 m.
	74 - 113 m	Schist.
	113 - 116 m	Quartzite.
	116 - 144 m	Schist, fractured at 119 m.
Depth:	144 m	
Water strikes:	53 m and 119 m.	
Final blow yield:	4.5 l/s	
Current use:	Production borehole.	

Aquifer properties		**Borehole yield (m^3/d)**	
T-early (m^2/d):	2	Recovery method:	30
T-late (m^2/d):	-	Late-T method:	-
T-recovery (m^2/d):	1.5	Drawdown-boundary:	21
S_f (estimate):	0.0001	Distance-boundary:	28
S_m (estimate):	0.001		
t/t' intercept:	1.3		
RWL-main water strike (m):	44	**Aquifer yield (m^3/d)**	
Dist.-boundary (m):	18		
Time-boundary (d):	1	Recharge:	-
Δh (m):	4	Storage:	-
Catchment area (km^2):	-	Throughflow:	-
Recharge estimate (mm/a):	1		
Abstractable % of recharge:	-		
Aquifer thickness (m):	65		
B/h success rate (%):	70	**Current yield (m^3/d):**	**47**
Aquifer width (m):	-		
Hydraulic gradient:	0.02	**Failed at (m^3/d):**	-

Discussion

The drawdown curve of this borehole (Figure 7.27) is very similar to that of KG 108. In this case, leakage occurs after about two hours of pumping. The main difference between the test pump curves of these two boreholes lies with the recovery test (Figure 7.28). Whereas in KG 108 the residual drawdown was 5.87 m after six days since the constant rate test was stopped, the residual drawdown in KG 109 was 0.55 m after 22.5 hours. This may be due to the difference in aquifer storage, as depicted by the thickness of the weathered zones. In KG 108 the thickness of the saturated weathered zone, as determined from the geological logs, is 22 m, whereas in KG 109, it is 65.4 m. Because of this is it is not necessary to be as cautious when recommending the production yield of borehole KG 109.

The abstraction data shows that the water level in the borehole dropped by 4.5 m over the ten months of regular use (Figure 7.29). With the available abstraction data it is difficult to tell whether this is a problem or not. If recharge to the aquifer which supports this borehole occurs on a yearly basis, and during the year of production the recharge was about average, then the current abstraction rate may well be too high. However, if recharge in this arid part of the country (MAP < 100 mm/a) takes place every five years or so after an abnormally high rainfall event, and the three year monitoring period was between such recharge events, then the current abstraction rate may not be too high. Also, if the saturated weathered zone is indeed about 65 m thick, then sufficient storage may exist to support the current yield during the years of no recharge.

The late-T method could not be applied because low-permeability boundary effects are not shown in the drawdown curve. The yields given by the drawdown-to-boundary and distance-to-boundary methods (20-30 m^3/day), appear to be conservative. The distance-to-boundary method should not really be applied to this borehole because of the difficulty in determining Δh in leaky conditions. In this case the Δh value of 4 m was obtained by taking the distance between the 18 m inflection point, where leakage effects were first noticed, and the start of the late-time segment of the drawdown curve (shortly after day one).

Although the recovery test's yield of 30 m^3/day could be closer to the borehole's sustainable yield, the method itself is questionable, given the sensitivity to the t/t' value. An extrapolation of the recovery curve could give t/t' values which vary between 1.1 and 1.8, thereby giving yields which range from 12 - 58 m^3/day.

The aquifer yield assessment methods could not be applied due to problems associated with defining the aquifer's area, recharge area and width.

Figure 7.27 Borehole KG 109: Constant discharge test

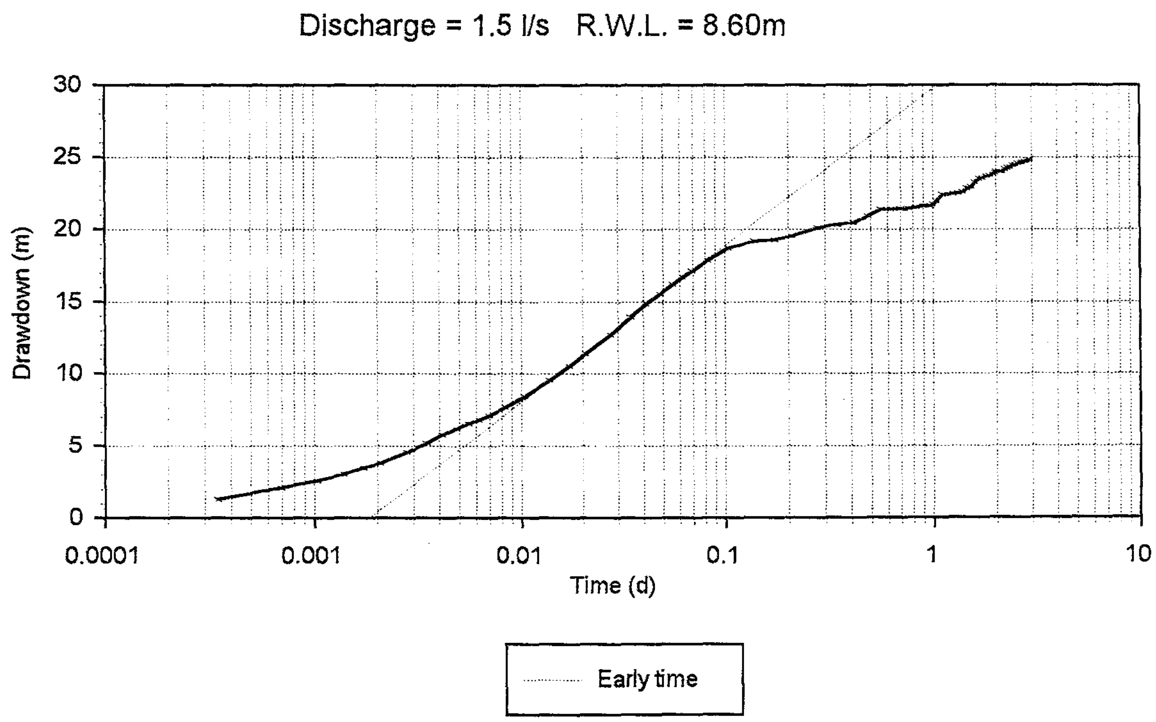


Figure 7.28 Borehole KG 109: Recovery test

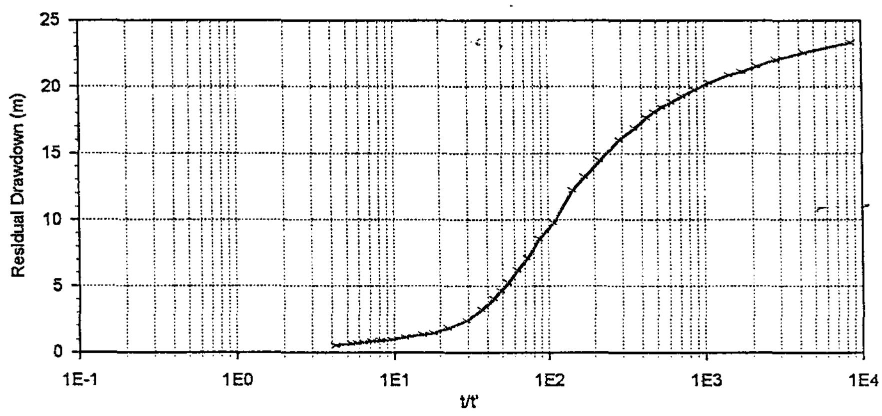


Figure 7.29 Borehole KG 109: Abstraction and water level data

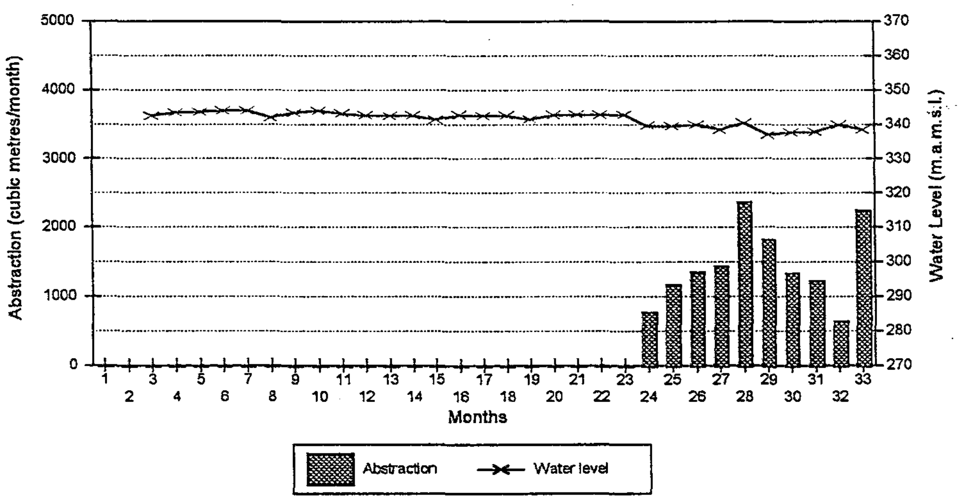
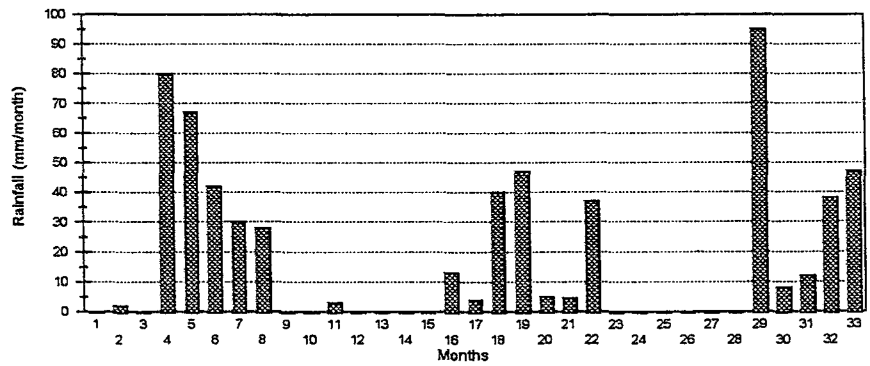


Figure 7.30 Borehole KG 109: Rainfall data



Borehole RV 205

Location:	Lekkersing, Northern Cape, South Africa	
Lithology:	Stinkfontein Formation, Gariep Complex.	
Geological log:	0 - 3 m	Alluvium.
	3 - 33 m	Fractured quartzite.
	33 - 38 m	Weathered Mudstone.
	38 - 43 m	Slightly weathered quartzite.
	43 - 76 m	Dolerite.
	76 - 87 m	Quartzite.
Depth:	87 m. The borehole is cased to 80 m, but records of where the slotted casing starts are not available.	
Water strikes:	1 - 43 m (Note: The rest water level matches the first water strike).	
Final blow yield:	20 l/s	
Current use:	Production borehole.	

Aquifer properties

T-early (m^2/d):	-
T-late (m^2/d):	36
T-recovery (m^2/d):	-
S_f (estimate):	0.0001
S_m (estimate):	0.001
t/t' intercept:	0.1
RWL-main water strike (m):	32
Dist.-boundary (m):	1.4
Time-boundary (d):	0.9
Δh (m):	0.2
Catchment area (km^2):	10
Recharge estimate (mm/a):	1
Abstractable % of recharge:	100
Aquifer thickness (m):	32
B/h success rate (%):	70
Years with no recharge:	3
Aquifer width (m):	400
Hydraulic gradient:	0.02

Borehole yield (m^3/d)

Recovery method:	0
Late-T method:	653
Drawdown-boundary:	26
Distance-boundary:	58

Aquifer yield (m^3/d)

Recharge:	27
Storage:	205
Throughflow:	288

Current yield (m^3/d): 30

Failed at (m^3/d): -

Discussion

According to the geological log, the first two metres of the drawdown curve represents the water level within the alluvium (Figure 7.31). Thereafter the borehole's water level is in the fractured quartzite, which due to its thickness in comparison to the alluvium, should be seen as the main aquifer. The aquifer system is unconfined, and leakage from the alluvium affects the drawdown curve up to about one day. After this period, the slope of the drawdown curve appears to be dominated by the fractured quartzite aquifer.

The abstraction data shows that the water level in the borehole dropped by 2.9 m over the two years of pumping, thereby dewatering the thin alluvial aquifer (Figure 7.33). During the last thirteen months of production where the average yield was 30 m^3/day, the water level dropped by 1.2 m. Like the other boreholes in this part of the country, their sustainable yields are related to how frequently and how much recharge the aquifers receive, and monitoring would have to cover the recharge cycles in order to establish the maximum long term production yield. Although the implications of continued abstraction from this borehole at this rate will only be known with further monitoring, it appears as if the aquifer can sustain this yield. It is however unlikely that a yield much greater than this can be sustained, because this borehole is not supported by a thick zone of weathered rock, like in the previous example.

The high available drawdown value used in the late-T method results in a dramatic over-estimation of this borehole's sustainable yield. If the thickness of the saturated alluvium was rather used as the available drawdown, a yield of 40 m^3/day would have been obtained. Although this yield is a lot closer to the current pumping rate, it could be slightly too high.

In the analysis of the drawdown-to-boundary method, it has been assumed that leakage from the alluvium dominates the drawdown curve up until day one of the constant discharge test. The distance to the boundary has therefore been taken as the point at which the late-time slope starts. This appears to be at a drawdown of 1.4 m, which is slightly below the point at which the late-time straight line slope intersects the drawdown curve. Using this s-value in equation 6.10 and the transmissivity of the quartzites (36 m^2/day), a reasonable yield of 26 m^3/day is obtained.

If it can be assumed that the slope between 0.3 - 0.9 days is not effected by leakage (which seems unreasonable given that the water level is still within the alluvium), an early-time transmissivity value of 86 m^2/day is obtained. Using this transmissivity value and an available drawdown of 0.9 m, the drawdown-to-boundary method gives yield of 38 m^3/day, which might be slightly high. The distance-to-boundary method should not be applied because it is difficult to establish a suitable Δh value. If however the transmissivity value of 86 m^2/day is used with a Δh value of 0.2 m, a yield of 58 m^3/day is obtained, which is possibly too high.

Of the aquifer yield assessment methods, the recharge method appears to give a reasonable answer. This may be because the conditions for using this method are good - the catchment area is relatively small and the water strikes fairly shallow.

Figure 7.31 Borehole RV 205: Constant discharge test

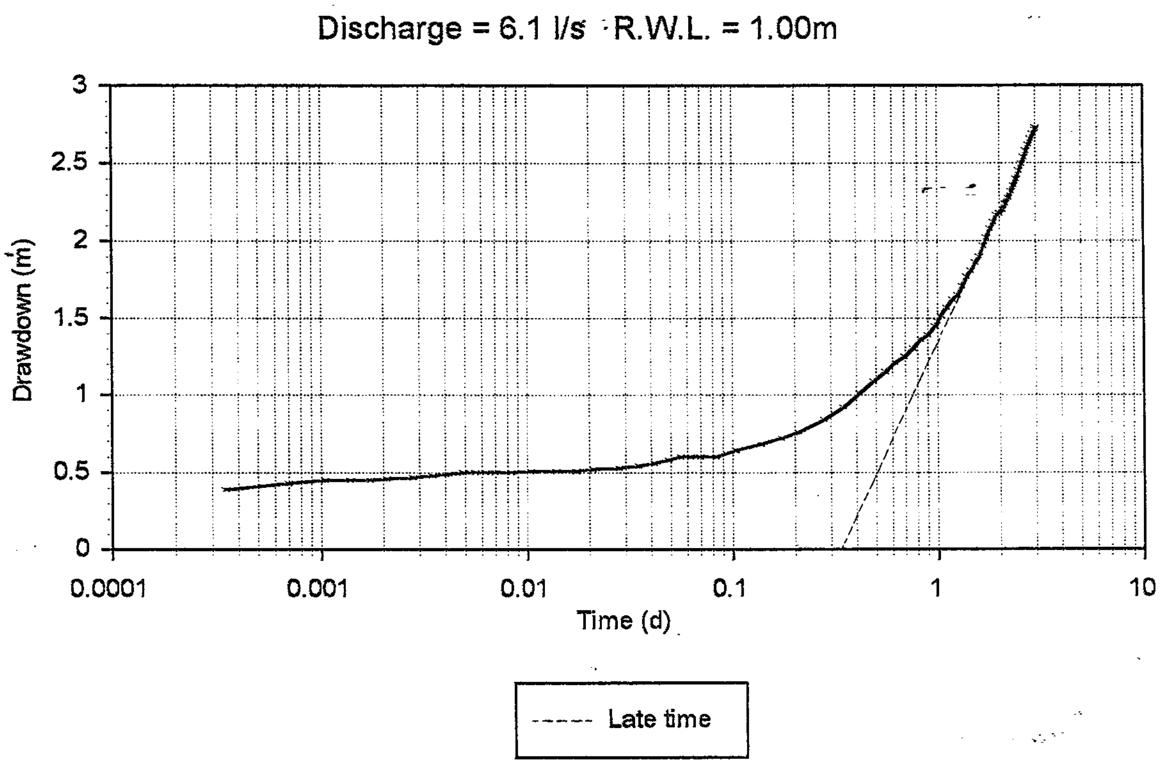


Figure 7.32 Borehole RV 205: Recovery test

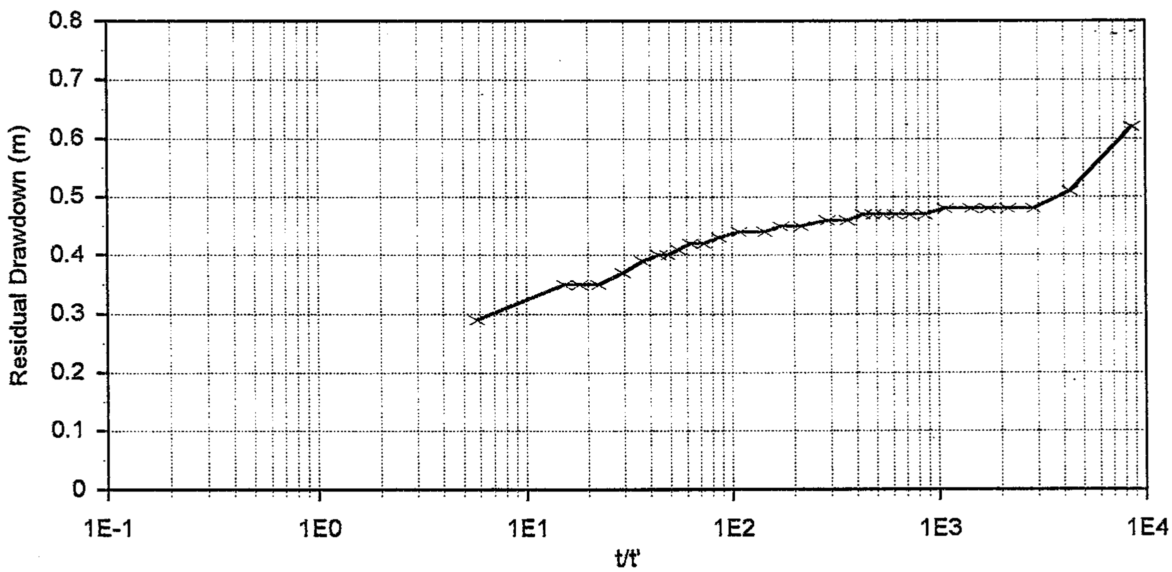


Figure 7.33 Borehole RV 205: Abstraction and water level data

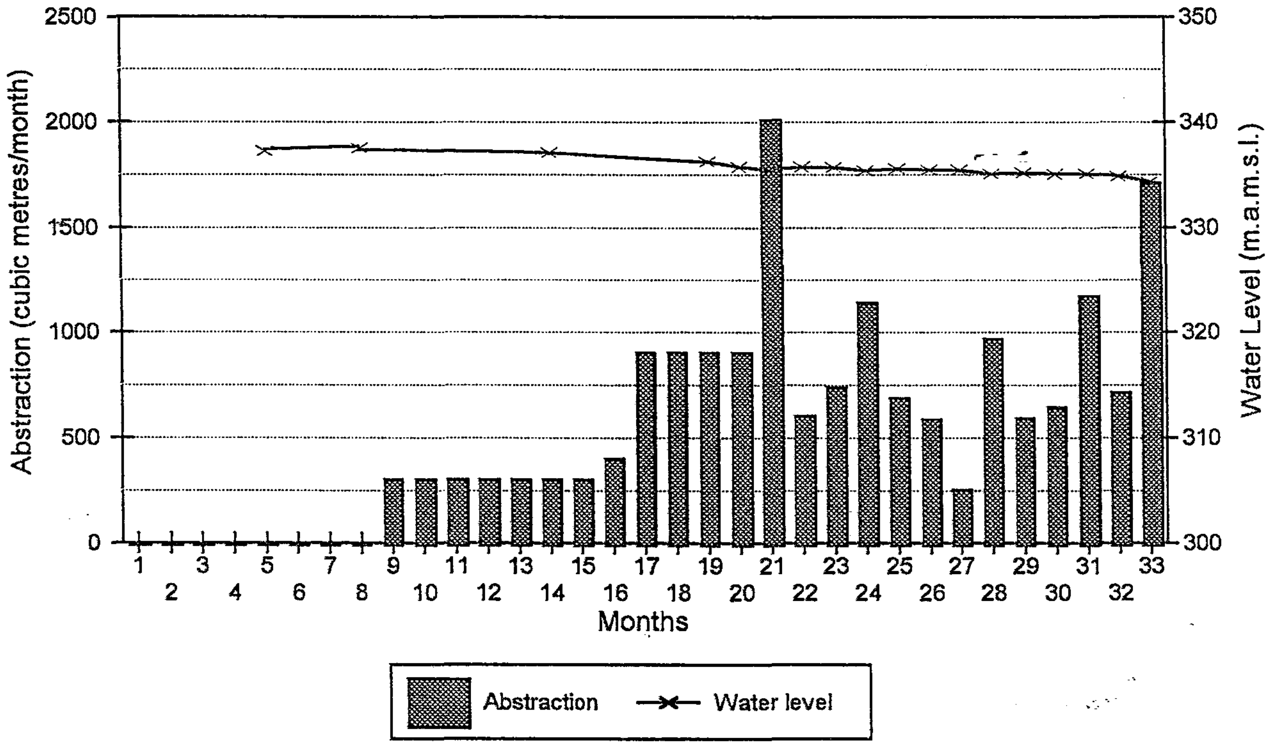
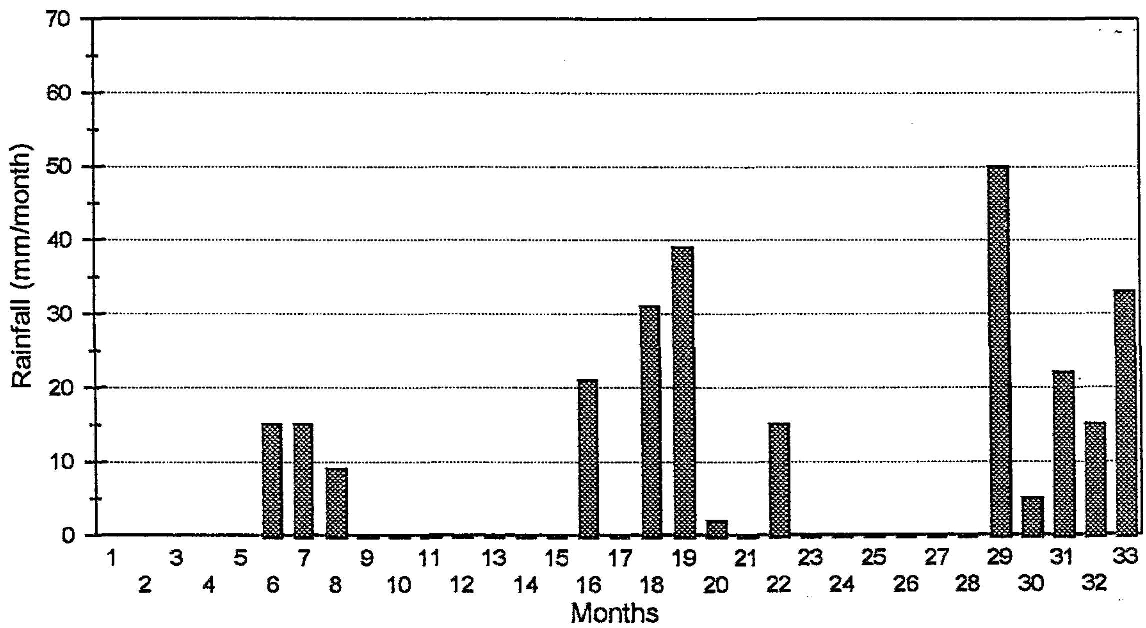


Figure 7.34 Borehole RV 205: Rainfall data



7.5 KARAGWE-ANKOLEAN SEQUENCE

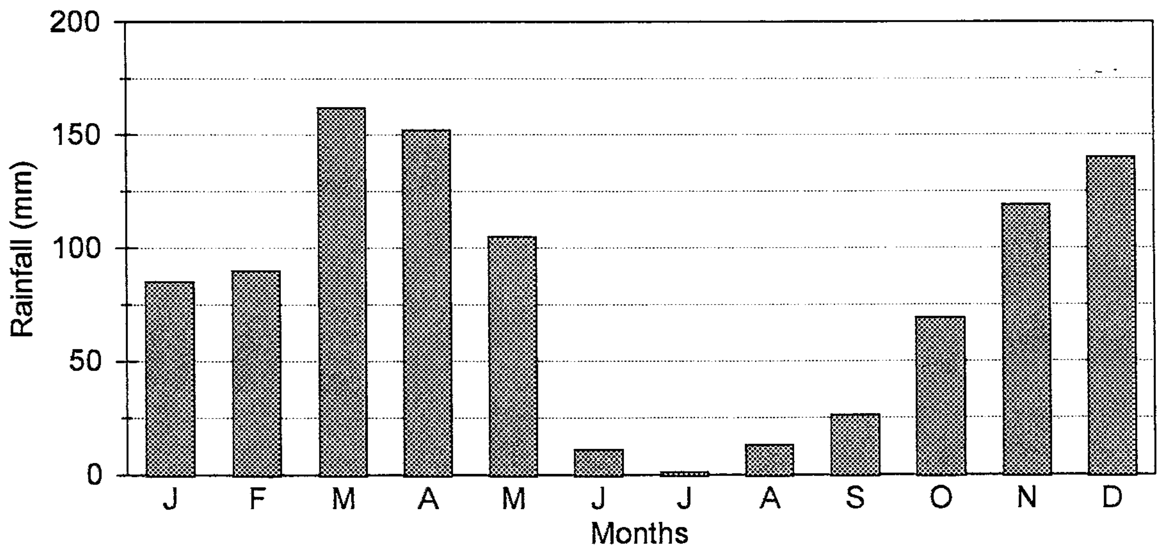
The boreholes studied in this section are located in the Ngara District in Tanzania, and are used to supply camps which have been set up to accommodate Rwandan refugees. A 24 hour constant rate test was conducted on the production boreholes, but no recovery data was collected. Water level and abstraction data have been collected for the nine productive months. Although this is an insufficient time period to establish the sustainable yield of the boreholes, it does however in some cases give a good indication of whether the current yields can be maintained. These graphs have been copied directly from the Austrian Relief Programme report because the field data was not presented in their report. The production boreholes were replaced due to design problems, and the geological logs of the replacement boreholes have been provided. The information used comes from the following reports:

Austrian Relief Program, July 1995. Borehole drilling for the refugee camps in the Ngara District.
Water Surveys Botswana, December 1994. Drilling for the Ngara Camps 14th October to 8th December 1994.
Water Surveys Botswana, December 1994. Further assessment of the quartzite aquifer around the Ngara Camps.

The aquifer yield methods can not be used because the boreholes are located within a 200 km^2 catchment.

Annual rainfall records exist for a station at Rulenge about 35 km from the camps. The mean annual rainfall is a little less than 1000 mm spread mostly between October and May (see Figure 7.35).

Figure 7.35 Average rainfall for Rulenge: 1990 - 1993



Borehole TN 14

Location:	Benaco, Ngara District, Tanzania.
Lithology:	Upper Division, Karagwe-Ankolean Sequence.
Geological log:	Unavailable. The water strikes were found in quartzites.
Depth:	102 m
Water strikes:	41 m, 55 m, 79 m. Main water strike at 79 m.
Final blow yield:	10 l/s
Current use:	Ex-production borehole. Taken out of production due to declining yield.

Aquifer properties		**Borehole yield (m^3/d)**	
T-early (m^2/d):	2.7	Late-T method:	95
T-late (m^2/d):	2.7	Drawdown-boundary:	17
S_f (estimate):	0.001	Distance-boundary:	31
S_m (estimate):	0.001		
RWL-main water strike (m):	55		
Dist.-boundary (m):	10	**Current yield (m^3/d):**	0
Time-boundary (d):	0.015		
Δh (m):	5	**Failed at (m^3/d):**	46

Discussion

The drawdown curve of this borehole (Figure 7.36) resembles that of Theis curve for confined conditions (Figure 6.1), and gives a transmissivity of 2.7 m^3/day. Double porosity or other boundary conditions are not evident within the duration of this 13 hour test, and therefore the slope can not be divided into early- and late-times. The abstraction and water level data show that the borehole failed after three months of regular pumping at an average of 46 m^3/day (Figure 7.37).

If the main water strike (79 m) is used to determine the available drawdown in the late-T method (which, strictly speaking should not be used because a late-time curve cannot be identified), an incorrect yield of 95 m^3/day is obtained. However, if the first water strike (41 m) is used a yield of 29 m^3/day is obtained, which is probably close to this borehole's maximum sustainable yield.

Although the distance-to-boundary method should also not be applied in this case because the drawdown curve does not show dual porosity or boundary effects, it gives a very similar yield to the late-T method (using the first water strike). A yield of 31 m^3/day is obtained if: the early time curve is defined as the slope between 5 - 10 m, which gives an early transmissivity value of 5 m^2/day; the time to the boundary is taken to be 0.015 days (22 minutes); and Δh is defined as 5 m.

The drawdown-to-boundary method probably gives a more realistic long-term production yield, so long as the boundary is defined as the point at which the drawdown curve starts its linear slope.

Figure 7.36 Borehole TN 14: Constant discharge test

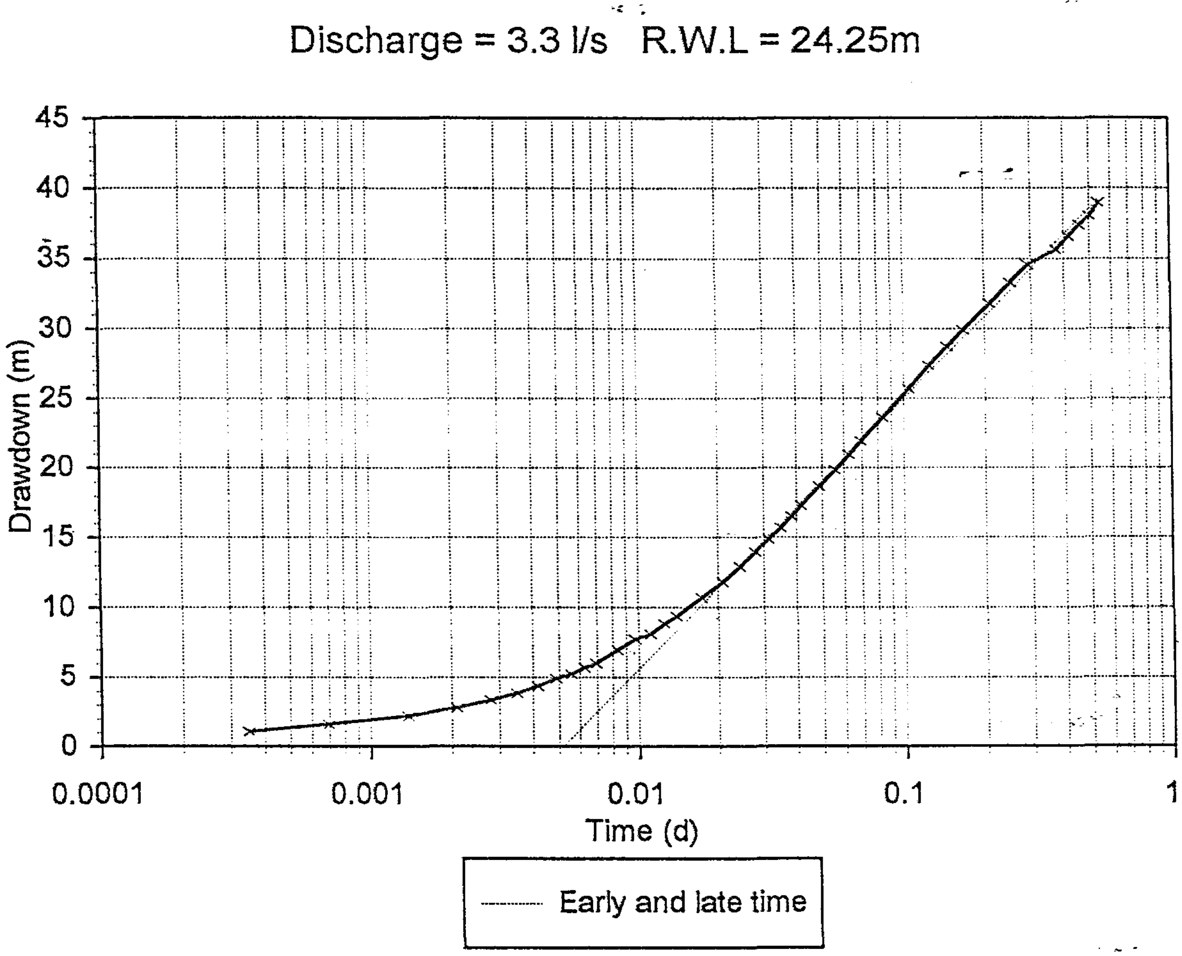
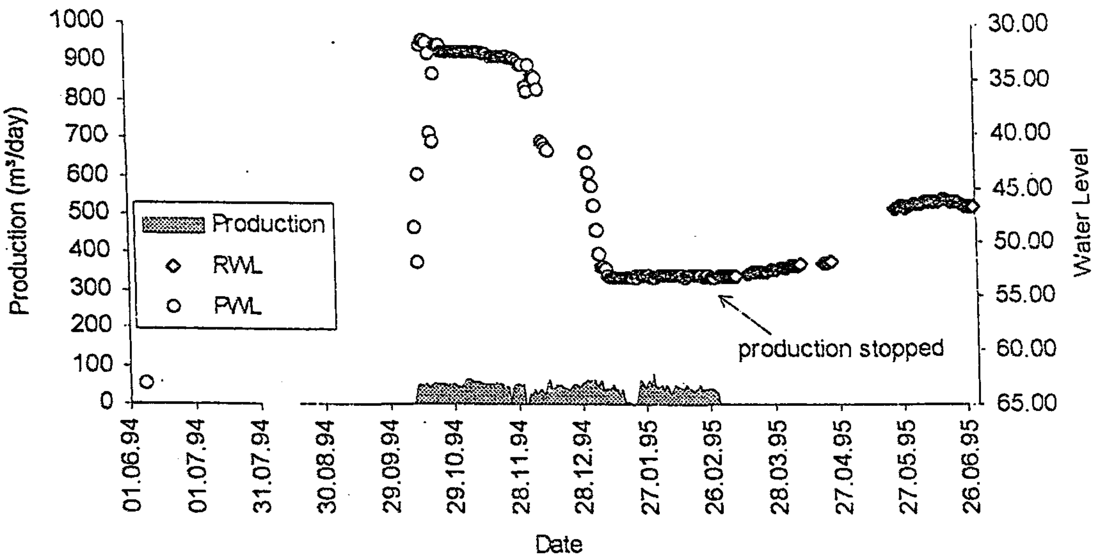


Figure 7.37 Borehole TN 14: Abstraction and water level data
(Source: Austrian Relief Program, 1995)



Borehole TN 15

Location:	Musuhura, Ngara District, Tanzania.	
Lithology:	Upper Division, Karagwe-Ankolean Sequence	
Geological log:	0 - 4 m	Clay
(of replacement borehole)	4 - 100 m	Shale (green, red and grey horizons), with thin quartzitic layers between 80 - 83 m
Depth:	100 m	
Water strikes:	61 m, 79 m. Main water strike at 79 m.	
Final blow yield:	6.9 l/s	
Current use:	Production borehole for Musuhura refugee camp.	

Aquifer properties		**Borehole yield (m^3/d)**	
T-early (m^2/d):	286	Late-T method:	1719
T-late (m^2/d):	52	Drawdown-boundary:	119
S_f (estimate):	0.001	Distance-boundary:	323
S_m (estimate):	0.001		
RWL-main water strike (m):	59		
Dist.-boundary (m):	0.8	**Current yield (m^3/d):**	±200
Time-boundary (d):	0.05		
Δh (m):	0.8	**Failed at (m^3/d):**	**317**

Discussion

The borehole penetrates steeply dipping shales and quartzites with near-vertical fractures, giving a drawdown curve (Figure 7.38) which resembles that of a pumped well in a fractured dyke (Figure 6.4). During the year of regular use with an average yield of 317 m^3/day, the water level in the borehole dropped by 30 m (Figure 7.39). This yield could not be sustained, so it was reduced to about 200 m^3/day, and is currently being monitored.

Without the recovery data to assist with this borehole's yield assessment, it is fairly difficult to recommend a sustainable abstraction rate. The late-T method clearly over-estimates the borehole's sustainable yield, due to the high available drawdown value used. If a Δh value of 0.8 m is used, the distance-to-boundary method also over-estimates the borehole's yield. The Δh value would have to be taken as 0.5 in order to obtain the more acceptable yield of 202 m^3/day. The drawdown-to-boundary method gives the most suitable answer, although it may be on the conservative side. Further monitoring is necessary to establish this borehole's sustainable yield.

Figure 7.38 Borehole TN 15: Constant discharge test

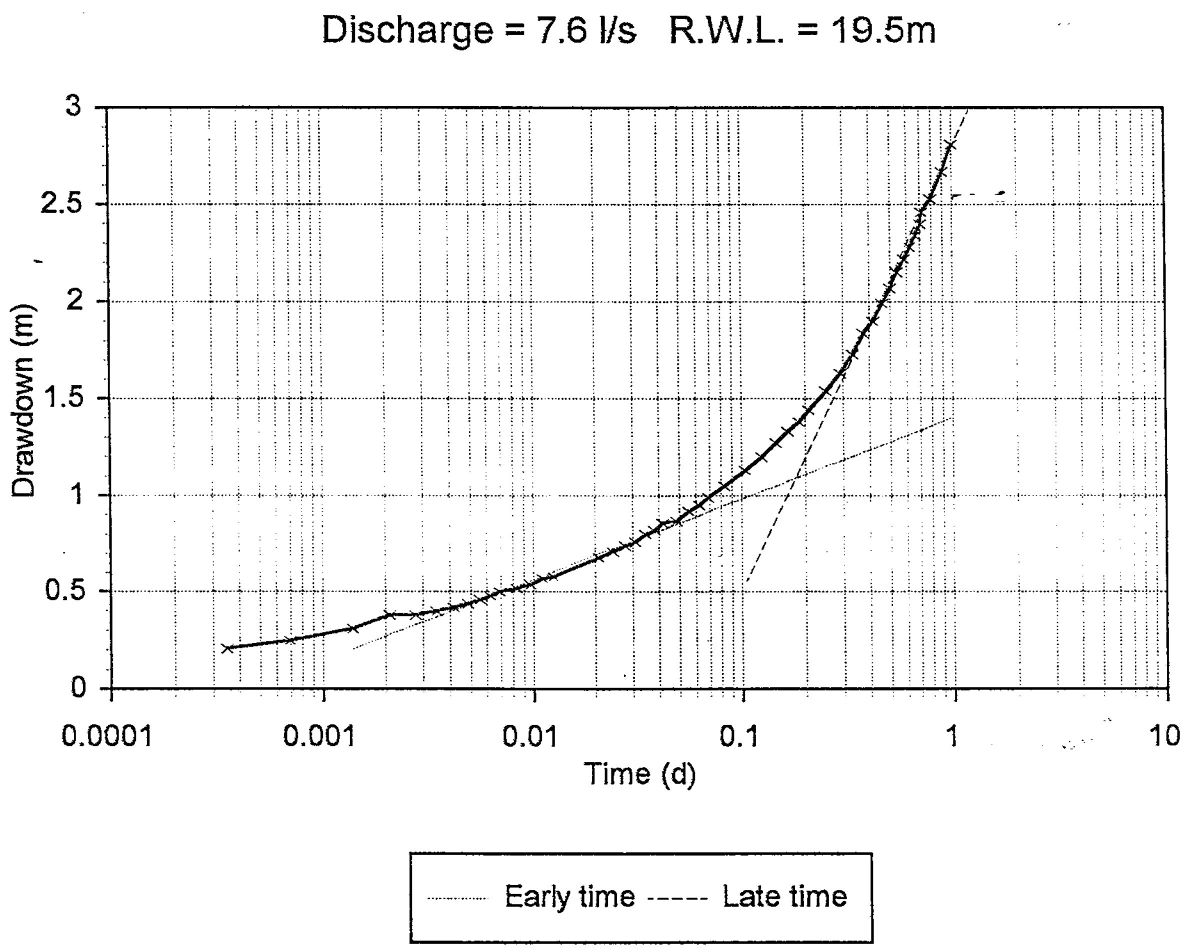
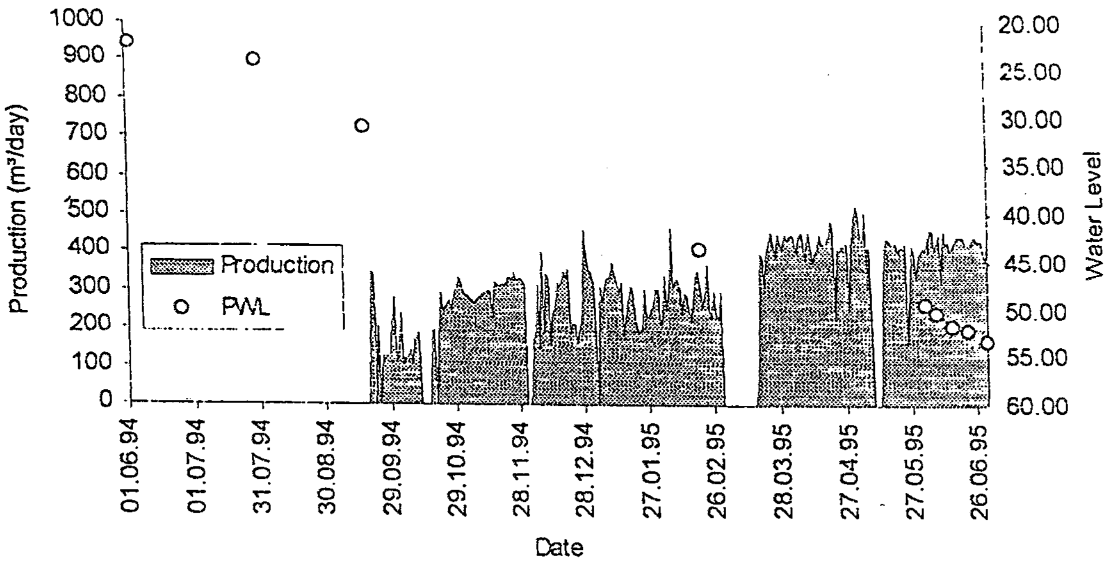


Figure 7.39 Borehole TN 15: Abstraction and water level data
(Source: Austrian Relief Program, 1995)



Borehole TN 16

Location:	Lumasi, Ngara District, Tanzania.	
Lithology:	Upper Division, Karagwe-Ankolean Sequence	
Geological log:	0 - 2 m	Clay
(of replacement	2 - 20 m	Green shale, fractured and highly weathered
borehole)	20 - 37 m	Red shale, highly weathered
	37 - 85 m	Grey shale, fractured and weathered.
Depth:	102 m	The replacement borehole was 85 m deep.
Water-strikes:	29 m, 61 m, 79 m. Main water strike at 79 m.	
Final blow yield:	6.9 l/s	
Current use:	Ex-production borehole for Lumasi refugee camp.	

Aquifer properties		**Borehole yield (m^3/d)**	
T-early (m^2/d):	33	Late-T method:	393
T-late (m^2/d):	10	Drawdown-boundary:	189
S_f (estimate):	0.001	Distance-boundary:	212
S_m (estimate):	0.001		
RWL-main water strike (m):	65		
Dist.-boundary (m):	10	**Current yield (m^3/d):**	320
Time-boundary (d):	0.02		
Δh (m):	5	**Failed at (m^3/d):**	-

Discussion

The drawdown curve (Figure 7.40) resembles that of a confined aquifer, or of a single plane, vertical fracture system (Figure 6.1). This borehole was taken out of production due to problems with iron bacteria clogging the borehole. Although abstraction was monitored for the five productive months (Figure 7.41), water level data was not obtained due to the inaccessible location of the borehole. The report on this borehole states that the water level recovered to within 4 m of the original water level (no recovery time period was given), that recharge to the aquifer is "reasonable", and that a yield of 300 m^3/day could probably be maintained for the next five months. From this it is difficult to determine its sustainable yield, however if it can be assumed that the water level reading after pump shut-down (4 m below the original water level), was taken once the water level had stabilised, then it is likely that the yield of 320 m^3/day was too high.

The yield given by the late-T method is probably too high. Like the previous two examples, high yields are obtained when this method is applied to cases where the available drawdown values are high. Both the drawdown-to-boundary and the distance-to-boundary methods appear to give reasonable yields. If the borehole did not have the iron bacteria problem, it would have been interesting to see if the sustainable yield was indeed about 200 m^3 /day, as predicted by the drawdown-to-boundary and the distance-to-boundary methods.

Figure 7.40 Borehole TN 16: Constant discharge test

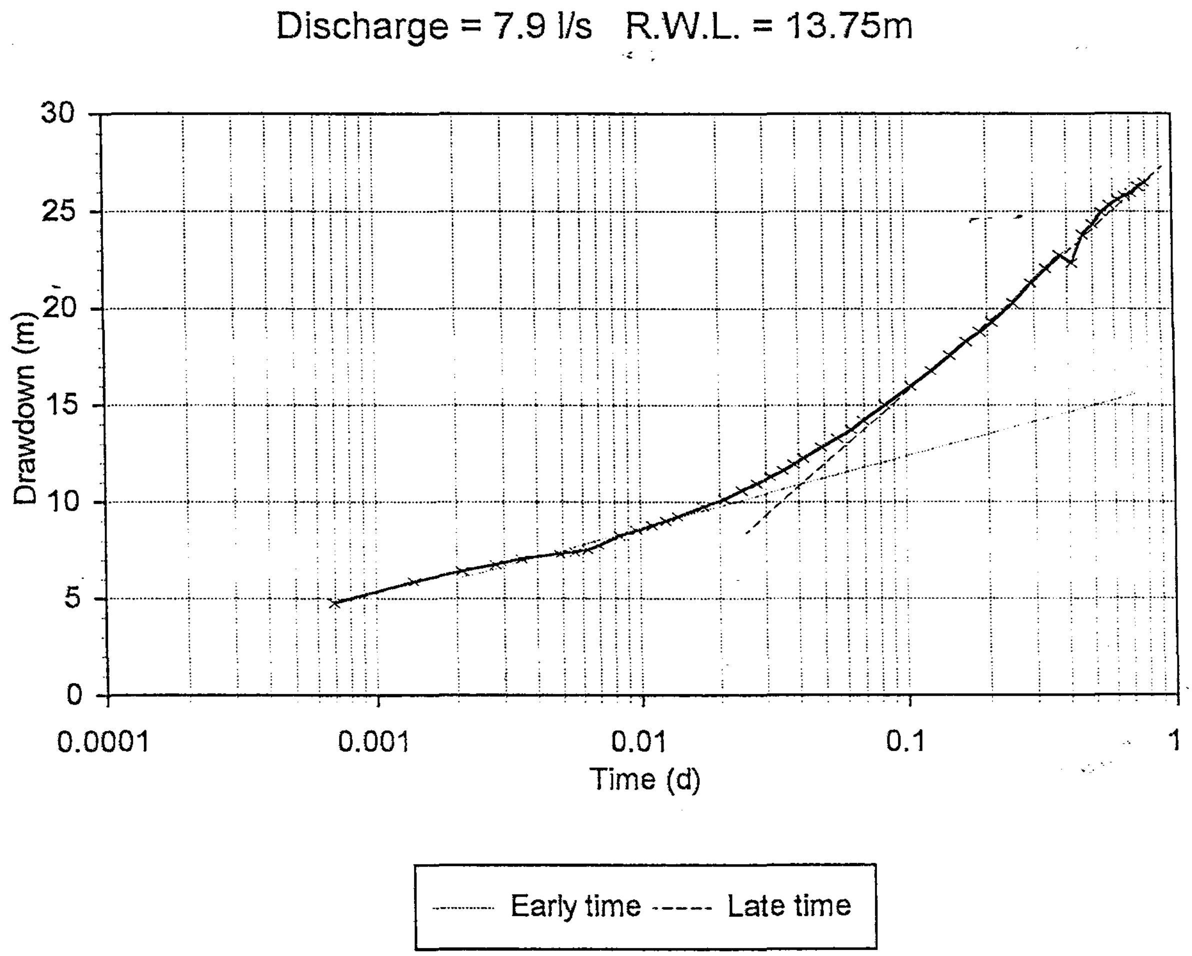
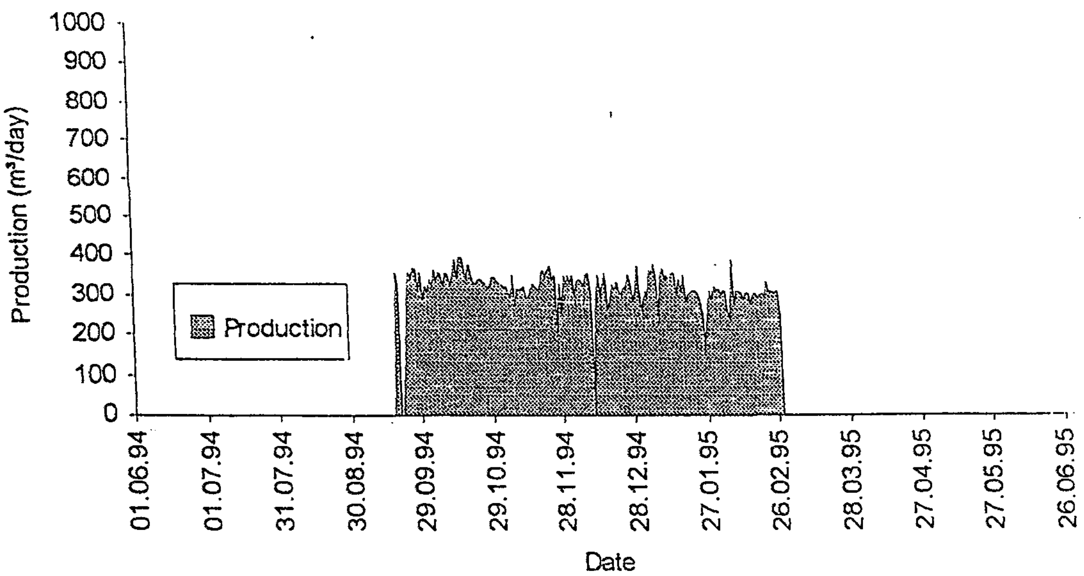


Figure 7.41 Borehole TN 16: Abstraction data
(Source: Austrian Relief Program, 1995)



Borehole TN 17

Location:	Lumasi, Ngara District, Tanzania.	
Lithology:	Upper Division, Karagwe-Ankolean Sequence	
Geological log:	0 - 12 m	Clay
(of replacement	12 - 72 m	Shale
borehole)	72 - 90 m	Phyllite
Depth:	102 m	The replacement borehole was 90 m deep.
Water strike:	78 m	
Final blow yield:	6.9 l/s	
Current use:	Production borehole for Lumasi refugee camp.	

Aquifer properties

T-early (m^2/d):	511
T-late (m^2/d):	257
S_f (estimate):	0.001
S_m (estimate):	0.001
RWL-main water strike (m):	64
Dist.-boundary (m):	1.54
Time-boundary (d):	0.3
Δh (m):	0.1

Borehole yield (m^3/d)

Late-T method:	8 604
Drawdown-boundary:	400
Distance-boundary:	92
Current yield (m^3/d):	**346**
Failed at (m^3/d):	-

Discussion

The drawdown curve deviates from its initial straight line after seven hours of pumping, indicating that a hydraulic boundary with a lower permeability was encountered by the cone of depression (Figure 7.42). The abstraction data shows that the water level in the borehole dropped by about 7 m over the seven months of regular use (Figure 7.43). This would suggest that the yield is not sustainable, however, with the three week break in production in April 1995, the water level rose nearly 5 m, indicating that recharge may take place rapidly after or during the high rainfall months of March and April. During the first month after pumping resumed the water level dropped by about 1.5 m, again indicating that the yield may be too high. This borehole would need to be monitored for a longer period in order to establish its sustainable yield, which could lie between 300 - 400 m^3/day.

The late-T method gives an unreasonably high yield due to the high available drawdown and high late-time transmissivity value used. Although the method was developed for fractured rock aquifers in general, of which this is an example, the authors imply that a late-time transmissivity value which reflects flow from the matrix to the fractures is needed (Kirchner and Van Tonder, 1995). In this example, the drawdown curve resembles that of a hydraulic boundary which is not of the double porosity type, and therefore the late-T value may be inappropriate. If the late-T method was indeed developed for dual porosity aquifers only, then this example shows how an unreasonably high yield can be obtained if the drawdown curve is misinterpreted as that of a dual porosity aquifer.

The drawdown-to-boundary method gives a reasonable yield assessment, although it may be on the high side. The distance-to-boundary method is difficult to apply because it is not easy to determine the Δh value.

Figure 7.42 Borehole TN 17: Constant discharge test

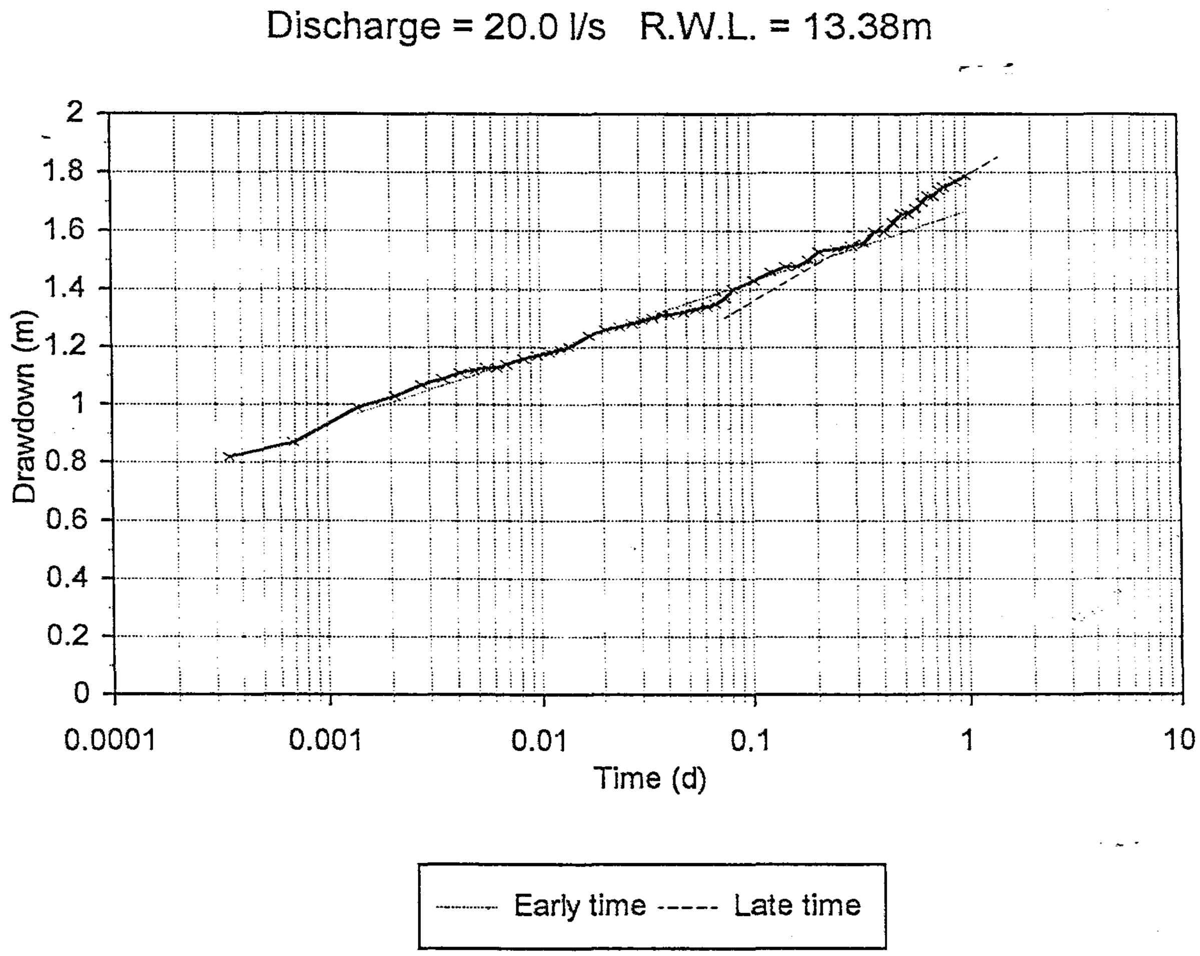
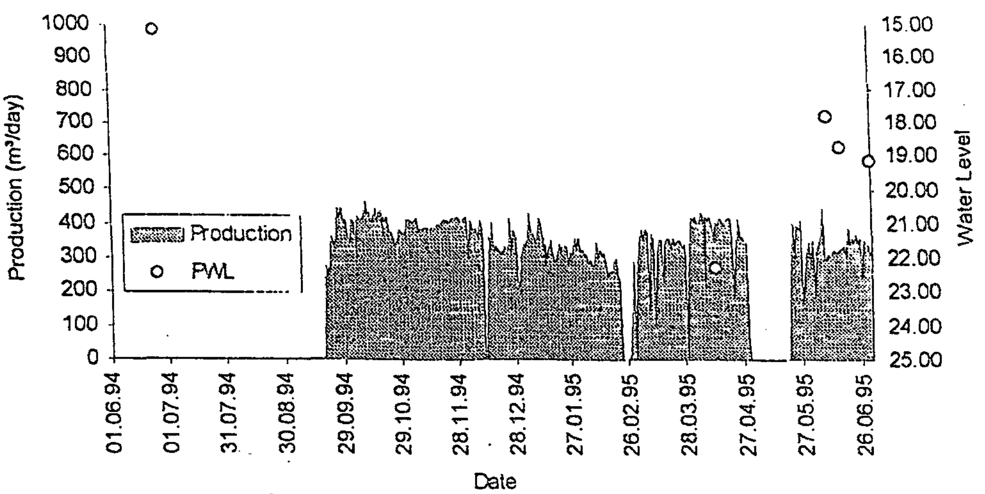


Figure 7.43 Borehole TN 17: Abstraction and water level data
(Source: Austrian Relief Program, 1995)



8. GUIDELINES FOR RECOMMENDING BOREHOLE ABSTRACTION RATES IN SECONDARY AQUIFERS

8.1 INTRODUCTION

Four methods for recommending borehole abstraction rates based on the interpretation of test pump data, and three methods based on an aquifer yield assessment have been presented and assessed. This chapter compares the results obtained in the previous chapter, and discusses the conditions under which each method should be applied.

8.2 A COMPARISON OF THE YIELD ASSESSMENT METHODS

In order to assess which yield assessment methods give acceptable long-term borehole yields that are not too conservative, it is necessary to know the maximum sustainable yields of the boreholes. As mentioned in the previous chapter, the borehole abstraction and water level data provided was in most cases insufficient to establish these yields. However, sufficient information exists to estimate the likely sustainable yield range for each borehole. This yield range was established after considering abstraction data, water level data (when available), and where necessary, test pump and aquifer yield analyses. Although the yield ranges are subjective, they nevertheless serve the purpose of illustrating which yield assessment methods give unacceptable results. Boreholes GR 2 and BRG 7 are used as examples to indicate how the sustainable yield ranges were obtained.

Borehole GR 2 is assumed to be the only borehole in the wellfield. The water level and abstraction data indicate that it was heading for failure at a yield of 665 m^3/day, and the yield of the aquifer was estimated to be 789 m^3/day (Smart, 1994). The borehole's upper range value was taken as 600 m^3/day. The water level data obtained since the production yield was reduced to an average of 181 m^3/day, indicates that this yield is conservative, therefore Woodford's recommended yield of 360 m^3/day was taken as the lower range value (Woodford, 1992). Although this range appears to be high, it clearly illustrates that the late-T method's yield of 1010 m^3/day is too high, and that the recovery method's yield of 0 m^3/day is unacceptable.

Borehole BRG 7 is located in a 1 km^2 catchment and failed at a yield of about 90 m^3/day. The abstraction rate had to be reduced dramatically to about 5 m^3/day in order to prevent pump suction from re-occurring. The range was taken as 5 - 15 m^3/day. Although the sustainable yield of this borehole may be higher than 15 m^3/day, of importance is that the throughflow method's yield of 137 m^3/day is obviously too high, and the yields obtained using the drawdown-to-boundary method, the distance-to-boundary method and the recharge method, which range from 6 - 11 m^3/day, appear to be acceptable.

Table 8.1 summarises the results obtained in the previous chapter, and includes the estimated yield ranges. These results are represented graphically in the forthcoming discussion on each method.

Figure 8.1 gives an overview of how each method fared in relation to the estimated yield ranges. Both the results for the full sample, and the selected sample where the conditions to apply the methods were met, are presented. From this it can be seen that out of the methods based on the constant discharge test, the drawdown-to-boundary method gave a suitable result in 93% of the cases, and the distance-to-boundary method, if correctly applied, gave a suitable result in 75% of the cases. Out of the methods based on an aquifer yield assessment, the recharge method gave a suitable result in all three of the cases which met the conditions for its application. All the other methods, when correctly applied, produced suitable results in less than 60% of the cases.

Figure 8.1 The percentage of borehole yields which fall within the estimated sustainable yield ranges

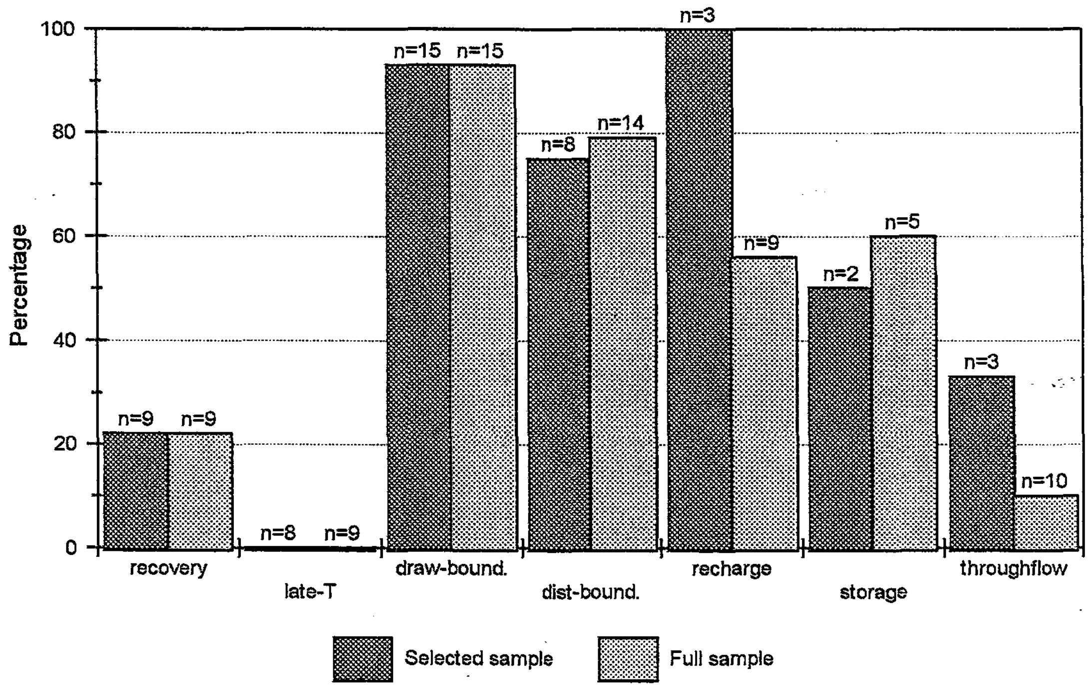


TABLE 8.1 **A comparison of the various borehole and aquifer yield assessment methods**

Numbers in bold refer to yields which fall within the estimated yield range (All values in m^3/day.)
Brackets mean that strictly speaking, the method should not have been used*.

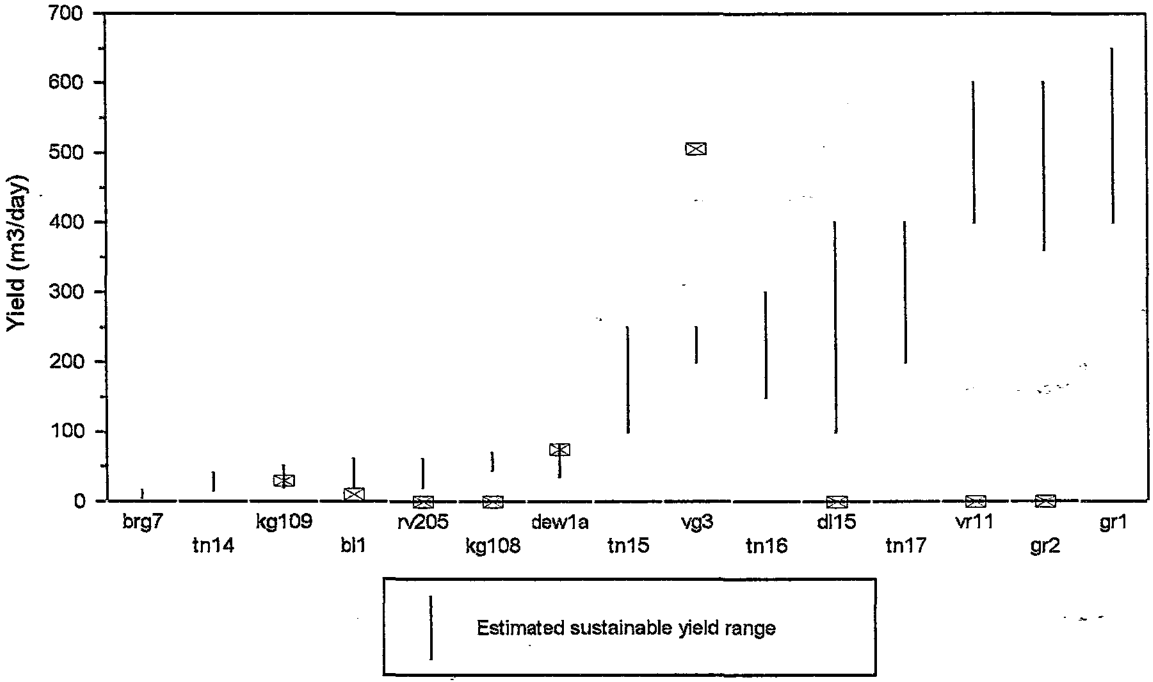
Method	GR 1	GR 2	BL 1	BRG 7	DEW 1A	DL 15	VR 11	VG 3	KG 108	KG 109	RV 205	TN 14	TN 15	TN 16	TN 17
Borehole yield analysis															
Recovery	-	0	10	-	**75**	0	0	507	0	**30**	0	-	-	-	-
Late-T	782	1010	-	-	-	512	813	-	-	-	605	(95)	1719	393	8604
Drawdown-boundary	**579**	775	**53**	**6**	**61**	**364**	**599**	**204**	**64**	**21**	**26**	**17**	**119**	**189**	**400**
Distance-boundary	**444**	**436**	**25**	**7**	-	**383**	**(480)**	**(242)**	**(99)**	**(28)**	**(58)**	**(31)**	323	212	92
Aquifer yield analysis															
Recharge	(173)	(173)	(105)	**11**	**50**	**(188)**	**(546)**	(384)	-	-	**27**	-	-	-	-
Storage	**(460)**	**(460)**	(22)	-	**73**	-	-	-	-	-	205	-	-	-	-
Throughflow	(158)	(82)	(13)	137	**37**	(64)	(75)	(35)	(27)	-	288	-	-	-	-
Long-term yield as estimated from abstraction and test pump data															
Lower yield	400	360	20	5	35	100	400	200	45	20	20	15	100	150	200
Upper yield	650	600	60	15	80	400	600	250	70	50	60	40	250	300	400

* For example, the distance-to-boundary method should not be used if the constant discharge drawdown curve is influenced by leakage, and a suitable Δh value can not be obtained.

8.3 THE RECOVERY METHOD

Figure 8.2 compares the yields obtained using the recovery method with the estimated sustainable yield ranges. Acceptable yields (those which fall within the estimated sustainable yield range) were obtained in two of the nine cases where the method could be applied, namely boreholes DEW 1A and KG 109. Neither of these yields were considered to be the most suitable, because they are the highest values that were obtained out of all the methods. However, it could be argued that the sustainable yield of these boreholes are unknown and that the yields obtained by the recovery method are suitable.

Figure 8.2 A comparison between the recovery method yields and the estimated sustainable yields



In cases where rapid recovery occurs due to leakage from overlying material or variations in storativity, high t/t' intercept values may be obtained. This results in suspiciously high yield recommendations, since the extent of storage in these horizons is not taken into account. Borehole VG 3 is a good example of how leaky conditions led to a high t/t' value, and an unreasonably high yield estimation. Recharge during the constant discharge test may also lead to high t/t' intercept values. Unless the recharge source is believed to be sustainable, the yield obtained from the recovery method would probably be too high.

In most cases a zero yield was obtained because the extrapolation of the recovery curve to the x-axis of the time - residual drawdown graph, gave a t/t' value of less than one. This does not mean that the borehole can not yield anything on a sustainable basis. Boreholes GR 2 and VR 11 have sustainable yields which are probably greater than 300 m^3/day, yet their yields obtained using the recovery method are zero.

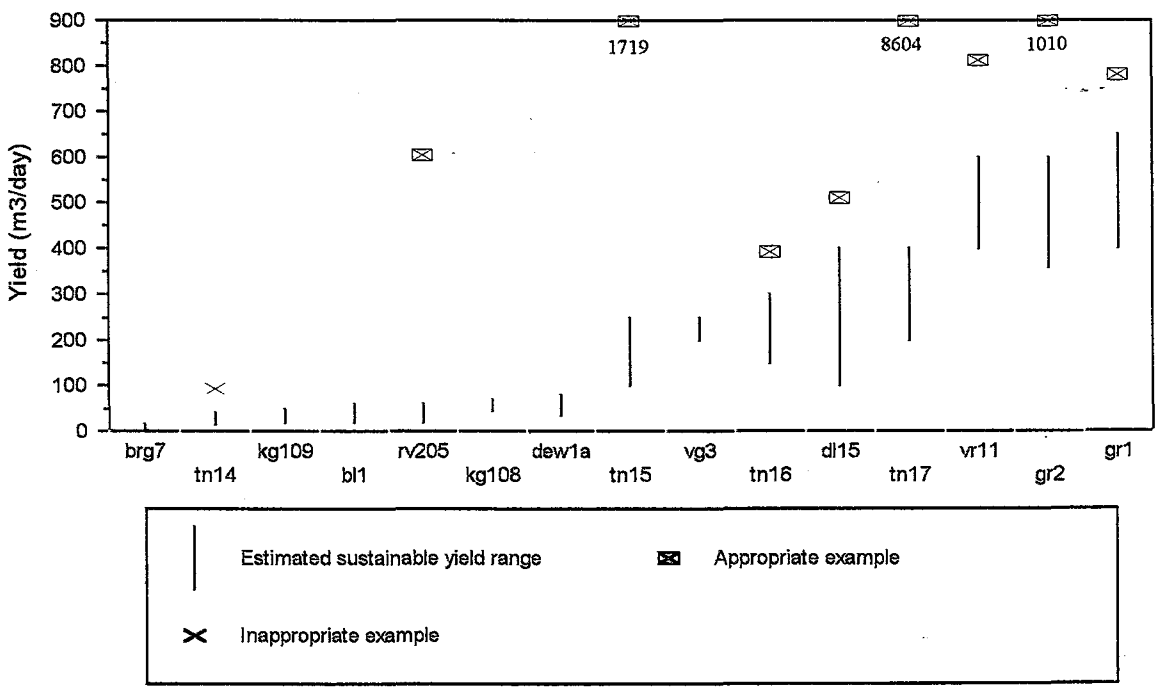
The yield obtained from the recovery method is highly sensitive to the extrapolation of the recovery curve, which in most instances gives non unique t/t' values. This drawback, together with the results presented, indicate that the recovery method should not be used to establish production yields. Rather, the recovery data should be used to determine whether it is necessary to be conservative when making yield recommendations which are based on other yield assessment methods. A long recovery period (where the extrapolation of the recovery curve gives a t/t' value of less than one), or incomplete recovery indicates that the aquifer is of a limited extent or that it consists of lower permeability boundaries. For this reason, a conservative yield recommendation may be necessary.

Borehole GR 2 is a good example of this. In this case a residual drawdown of 3.88 m was recorded three days after the constant rate test had stopped, correctly indicating that a conservative yield estimate should be made. Only the yield assessment methods based on test pump data could be applied in this case, of which the distance-to-boundary method gave the lowest yield - a value which seems reasonable after assessing the monitored data.

8.4 THE LATE-T METHOD

All of the yields obtained using the late-T method were higher than the estimated upper sustainable yields. Some were significantly higher, like the yields obtained for boreholes RV 205, TN 15, TN 17 and GR 2 (Figure 8.3). Appropriate examples in Figure 8.3 refer to those cases for which the method was developed. In relaation to the late-T method, this meant that the drawdown curve could be divided into early- and late-times, with the late-time transmissivity being significantly less than the early-time transmissivity. A suitable late-time transmissivity value could not be established for borehole TN 14, therefore it is described as an inappropriate example.

Figure 8.3 A comparison between the late-T method yields and the estimated sustainable yields



The concept of using transmissivity that reflects steady-state flow from the matrix to the fractures seems reasonable when assessing borehole yields in fractured rock aquifers. However, it may not be possible to determine whether the late-time segment of the drawdown curve reflects only inter-porosity flow or other boundary conditions, as more than one hydrogeological environment can produce similar late-time drawdown curves.

Kirchner and Van Tonder (1995) state that the difference between boundary and double porosity effects can be recognised by the shape of the late-time drawdown curve: a barrier boundary in a radial flow system will cause at the most a doubling of the drawdown slope after boundary conditions have been encountered, and double porosity effects will cause a far greater increase in slope. While a single boundary may cause the drawdown slope to double, the water level in a borehole which penetrates an aquifer of limited extent could plummet to the bottom of the borehole once the cone of depression dewaters the most permeable fractures, thereby resulting in a 'steep' late-time slope. The late-T method requires the late-T value to reflect steady state flow from the matrix to the fractures. This may be difficult to establish considering the various hydraulic conditions which can cause a 'steep' late-time drawdown slope.

If this method was intended for cases where the late-time drawdown slope is greater than twice the early-time slope, it should only have been applied to boreholes GR 2, DL 15, VR 11, TN 15 and possibly TN 16. These boreholes all penetrate fractured rock aquifers, and flow from the matrix or micro-fissures to the fractures is likely to have been induced during the constant drawdown tests. In all of these cases the late-T method gave the highest value out of the three methods which are based on the Cooper-Jacob equation (eq.6.10). Not surprisingly, the boreholes which gave yields closest to the estimated maximum sustainable yields, were those with the lowest late-time transmissivity values (10 m^2/day or less).

The main reason for the relatively high yields obtained using this method, is that it uses the distance between the rest water level and the main water strike as the available drawdown. The yield obtained using the Cooper-Jacob equation is directly proportional to the available drawdown value that is used, and in confined fractured rock aquifers this value can be substantial. For example, the distance between the rest water level and the main water strike in the three Cape Supergroup examples are 75 m, 104 m and 128 m. While the sustainable yield of a borehole may be influenced by the depth of the main water strike, because the deeper the water strike, the greater the permissible drawdown and the cone of depression's area of influence, it is unlikely that these factors are directly proportional. Another drawback with the method is that it allows for the entire available drawdown to be pumped in a given year, thereby unreasonably assuming that annual recharge will result in its complete replenishment.

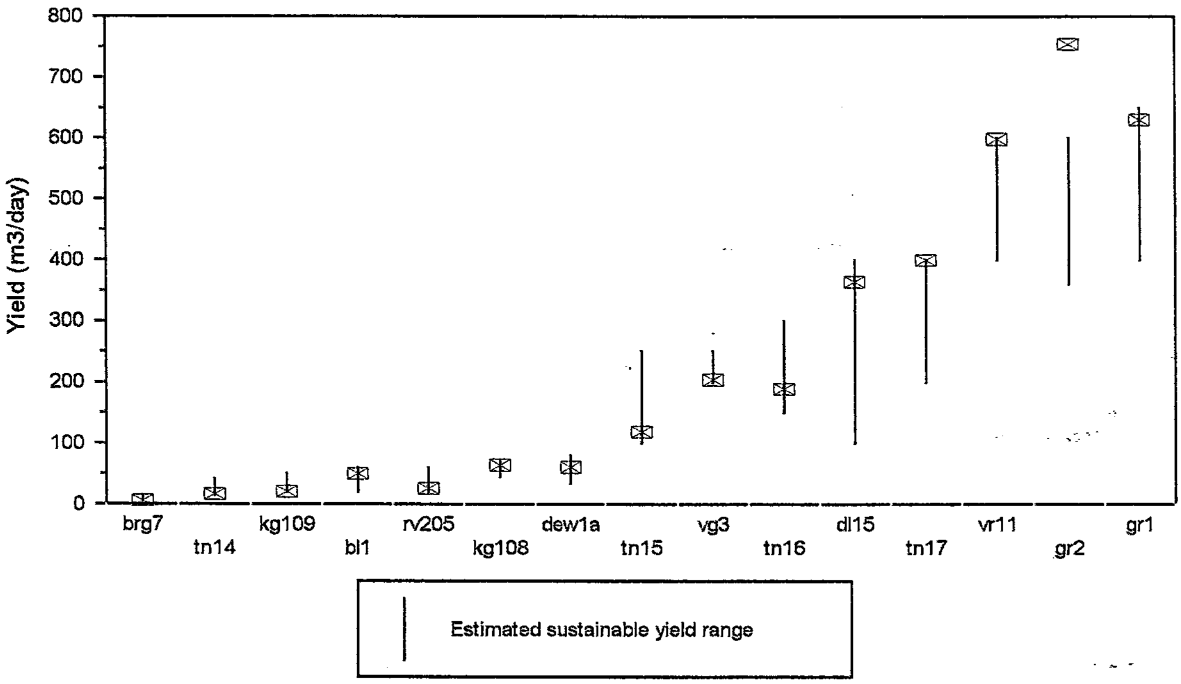
Although it may appear as if the method should be discarded altogether, this is not the case, as it can be modified to give lower yields in cases where a more conservative value is needed. This may be necessary where incomplete recovery is experienced after the constant rate test, or where the main water strike is very deep. In such cases, instead of using the main water strike as the reference point on which to obtain the available drawdown, the first water strike could be used. If the first water strike is used in boreholes GR 1, GR 2 and TN 14, acceptable yields are obtained (469 m^3/day, 337 m^3/day and 30 m^3/day respectively), whereas if the main water strikes are used, the yields are clearly over estimated.

It would appear as if this method could be applied with a fair degree of accuracy in cases where the water strikes are not far below the rest water level (possibly within or slightly below the weathered formation in aquifers where the bulk of the storage lies within this zone), and where the late transmissivity values are not too high. Unfortunately no guideline as to what constitutes reasonable available drawdowns and late-time transmissivity values can be given.

8.5 THE DRAWDOWN-TO-BOUNDARY METHOD

The drawdown-to-boundary method was the most reliable method, giving a suitable result in all but one of the cases (Figure 8.4).

Figure 8.4 A comparison between the drawdown-to-boundary method yields and the estimated sustainable yields



In the case of borehole GR 2, where the sustainable yield was over estimated, the method should have been adapted to give a lower yield because of the incomplete recovery experienced after the constant discharge test. In this instance, the thickness of the saturated weathered zone, or the first inflection point on the drawdown curve (6 m in Figure 7.1) rather than the second one should have been used in determining the available drawdown. Had this been the case, an acceptable yield of 423 m^3/day would have been obtained. As noted in the discussion on borehole GR 2 in the previous chapter, the available drawdown to the first inflection point matched the thickness of the saturated weathered zone.

Unfortunately there was insufficient detail in the geological logs supplied to determine how reliable it would be if the thickness of the saturated weathered zone was used generally to determine the available drawdown in the Cooper-Jacob equation (eq.6.10). One concern in using the constant discharge test in high yielding boreholes for determining the thickness of the saturated weathered zone, is that the water level in the borehole could be drawn down below this zone very rapidly due to the relatively low permeability of this layer, and the early inflection point could be missed. This problem could possibly be overcome by conducting multiple discharge tests using fairly low yields in the early steps.

In areas where the aquifer's storage can essentially be defined as the saturated weathered formation, the concept of using the thickness of this zone as the available drawdown in the Cooper-Jacob equation seems acceptable. In these circumstances it would not be desirable to draw the water in the borehole below this level, as this could result in the dewatering of the aquifer.

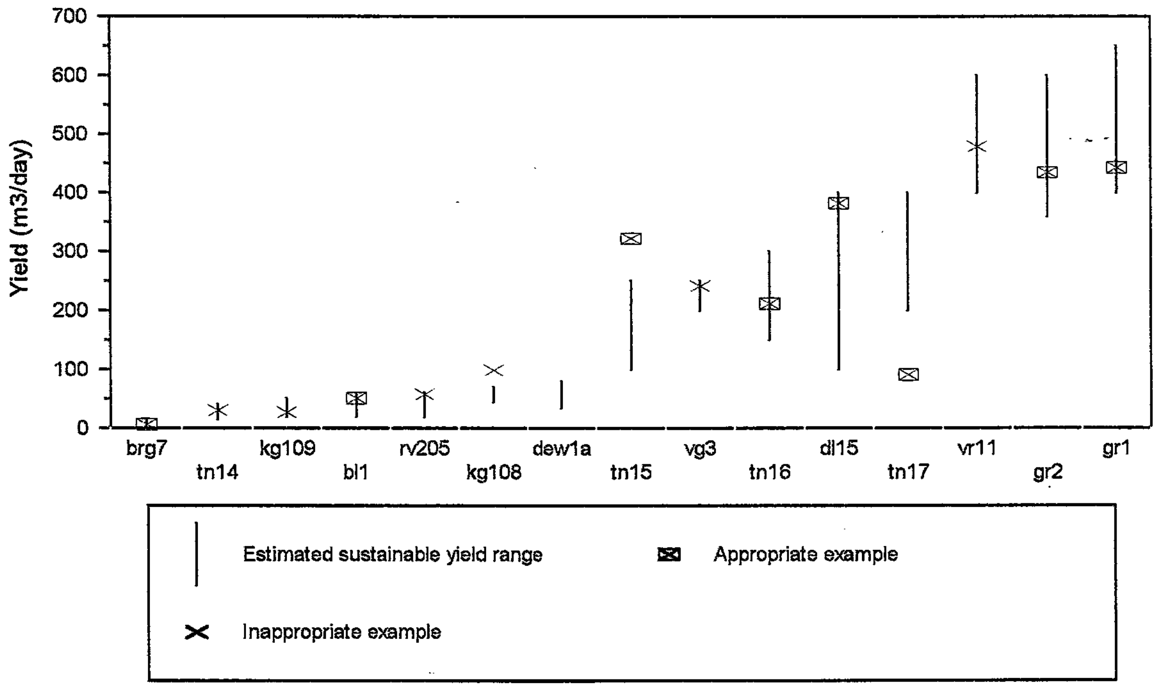
The distance to the inflection point on the drawdown curves in both the Karoo and the Karagwe-Ankolean cases, was less than 11m. For the Karoo examples, the average distance was 6.3 m. Although the sample for Karoo aquifers is inadequate to make generalisations about available drawdown values to use in the Cooper-Jacob equation, these results show that it might be worth being cautious if values much greater than 10 m are obtained.

The drawdown-to-boundary method is easy to apply, and from this study which covered various secondary aquifers, it gave acceptable results. It may be necessary to be conservative when using this method in cases where incomplete recovery is experienced after the constant rate test, or in cases where the thickness of the main aquifer that supports the borehole (commonly the saturated weathered zone) is limited.

8.6 THE DISTANCE-TO-BOUNDARY METHOD

Figure 8.5 shows how the values obtained using the distance-to-boundary method compare reasonably well with the estimated sustainable yield ranges.

Figure 8.5 A comparison between the distance-to-boundary method yields and the estimated sustainable yields



Although this method gave acceptable results in eleven out of the fourteen cases it was applied to, it should only be used when the drawdown curve shows double porosity or boundary effects. Under these conditions an accurate Δh value can usually be obtained, which is essential because of the sensitivity of the result to this value in the Cooper-Jacob equation (eq.6.10). Determining the Δh value is the biggest problem with the method. Similar criticisms relating to the available drawdown value used which were levelled at the late-T method could be applied to this method - the yield obtained is directly proportional to the Δh value.

In the examples from Karoo aquifers, the Δh value was never greater than 1m, and if the guidelines are followed, this value should be obtained with a fair degree of accuracy. It should not be possible, for example to obtain a Δh value which is twice the 'correct' value. Although a ceiling-Δh value could not be obtained for Karoo aquifers because of the small sample, the results of this study indicate that one should be cautious if values greater than 1m are obtained.

The method should not have been applied to the Namaqualand / Gariep Complex boreholes, and it could only be correctly applied to one of the Cape Super Group boreholes, namely DL 15. The most common problem was because of leaky conditions, which make it difficult to determine the Δh value. Even in the case of DL 15 the room for error in establishing the Δh value is large.

In the case of the Karagwe-Ankolean Sequence boreholes, the method gave an acceptable answer in one of the three cases in which it should have been applied. Strictly speaking this method should not have been applied to borehole TN 14 because the drawdown curve does not show double porosity or boundary effects. In the case where a suitable answer was obtained (TN 16), Δh was 5m - a relatively large value in comparison to Karoo aquifers.

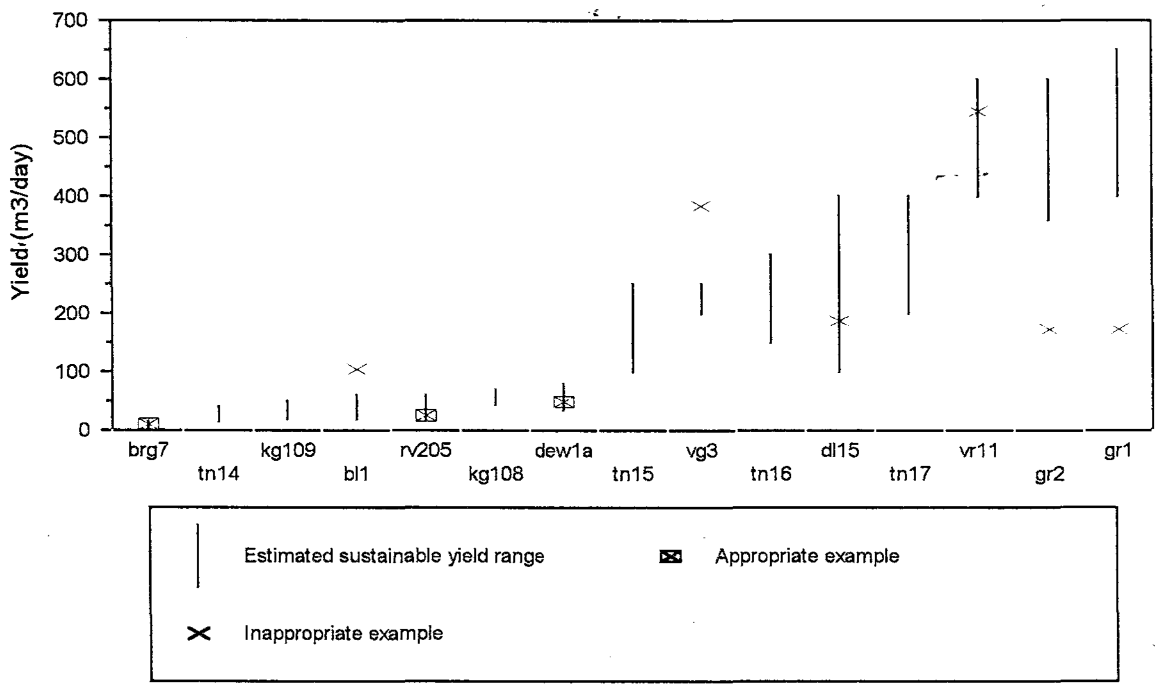
The study shows that the distance-to-boundary method can be successfully applied to Karoo aquifers, however, if a Δh value of more than 1m is used, the yield obtained may be too high.

8.7 THE RECHARGE METHOD

The recharge method which was developed in order to establish an estimate of a borehole's yield potential based on an aquifer yield, should only have been applied to three of the fifteen examples given, namely BRG 7, DEW 1A and RV 205. In all the other cases either the recharge area was too large or the depth of the water strikes was too deep for this method to be applied correctly. The method relies heavily on determining the recharge area - something which can only be done with an acceptable degree of accuracy in cases where the catchment area above the borehole is relatively small and where the borehole's water strikes are not too deep. Of the three cases mentioned, the largest catchment area was 13 km^2 and the deepest water strike $\pm$ 50m.

All three of the cases which meet the requirements to apply this method gave acceptable results (Figure 8.6). Although this sample is inadequate, it does however indicate that the method can be used to verify the results obtained from the methods based on test pump data.

Figure 8.6 A comparison between the recharge method yields and the estimated sustainable yields



This method gave acceptable results in two of the three Cape Supergroup examples where the catchment areas are within 12 km^2, and where the water strikes are over 100m deep. Although the water strikes are deep and therefore it would normally not be possible to easily determine the recharge area, the reason for the two acceptable results could be due to the steep topography and folded formations. This geological environment could confine the recharge area to the topographical divide.

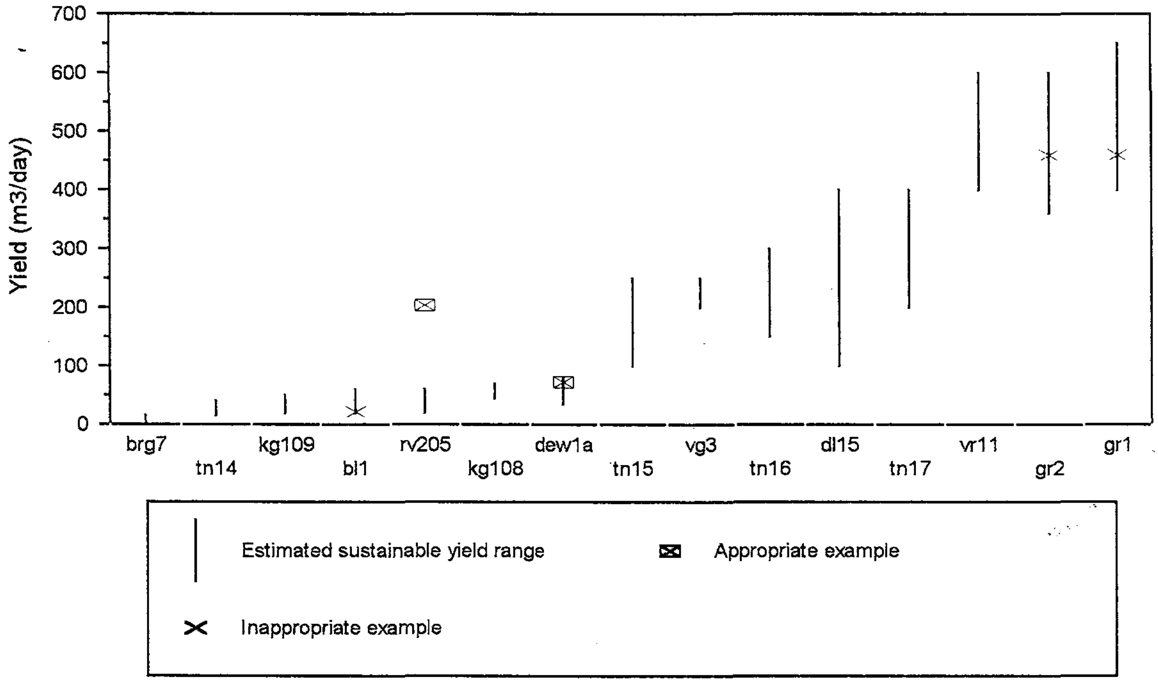
The recharge method gave acceptable results in 56% of the examples which include large catchments and deep water strikes. The method should not however, have been used in such conditions due to the error margins that could be introduced in determining the recharge area.

From these results, it is apparent that this method could be used to establish an estimate of a borehole's yield potential, if the borehole is located within a catchment of not much more than 10 km^2, and if water was struck no more than about 50 m below ground level. The method should, however, only be used if there is sufficient reason to believe that all the values used are likely to be representative of the study area.

8.8 THE STORAGE METHOD

One of the two cases which meet the requirements to apply this method gave an acceptable result (Figure 8.7).

Figure 8.7 A comparison between the storage method yields and the estimated sustainable yields



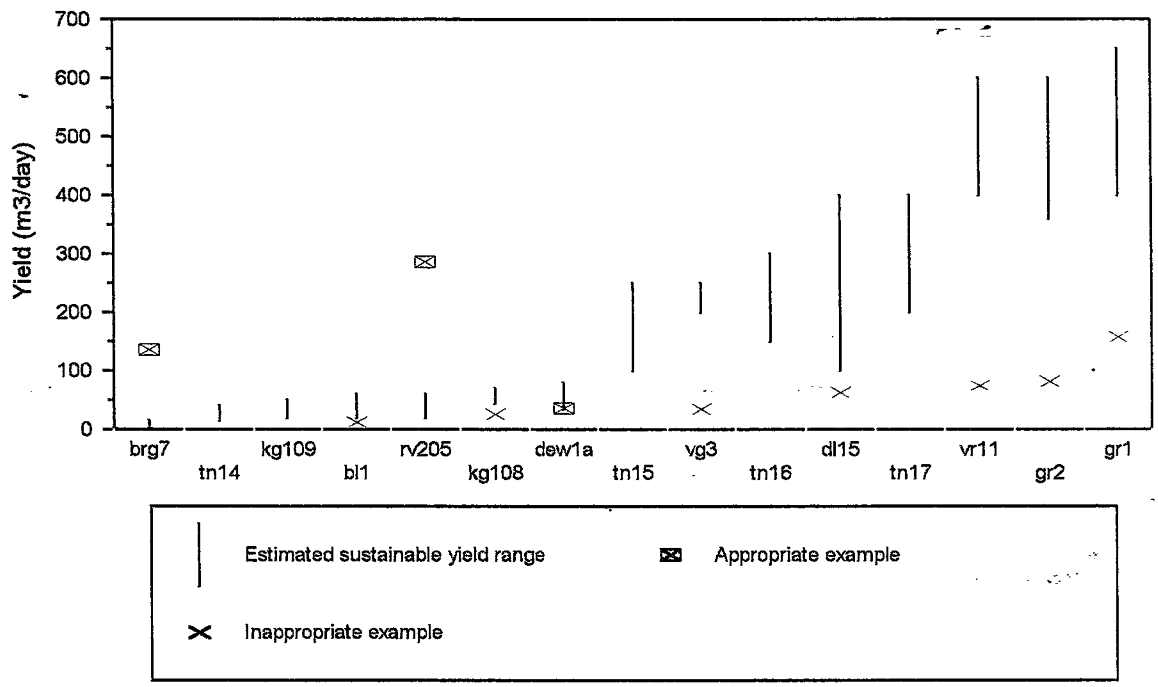
The margin for error in this method is high because it is sensitive to numerous factors which are difficult to quantify. Acceptable values for the aquifer's area, thickness and storativity are all virtually impossible to obtain in cases where only a single well exists, and the storativity value used could easily be an order of magnitude in error. Error is also introduced by estimating the number of years with no recharge and in the determination of the abstractable proportion of groundwater.

This method should only be used to obtain a rough estimate of the groundwater resource available to a borehole when sufficient, quality information is available, and when the aquifer is relatively small. In the only appropriate case where the method gave an acceptable result, the aquifer's area was 13 km^2.

8.9 THE THROUGHFLOW METHOD

This method gave an acceptable yield in one case, namely borehole DEW 1A (Figure 8.8).

Figure 8.8 A comparison between the throughflow method yields and the estimated sustainable yields



In the case of borehole DEW 1A the necessary aquifer parameters had been established (Kirchner et al., 1991), and the value obtained for the abstractable proportion of groundwater proved to be accurate. This shows that this method can be used to give an indication of a borehole's yield potential if the aquifer's parameters are properly defined.

The Graaff Reinett examples show why this method should not be used unless the necessary aquifer parameters are clearly defined. Boreholes GR1 and GR 2 are located less than 800 m apart in an aquifer which has an estimated width of 7000 m. Because their transmissivity values differ (as obtained using the late-time slope of the constant discharge test), so their yields based on this method differ. In this case, the one yield obtained is twice that of the other.

While it may be possible to estimate the width of the aquifer and it's hydraulic gradient (based on surface gradients in gentle slope conditions), it is problematic to assume that a mean transmissivity of the aquifer across the seepage face can be obtained from a single test pump analysis. This method is very sensitive to aquifer width, hydraulic gradient and transmissivity, and therefore should only be used when representative values have been obtained.

8.10 CONCLUSIONS

This study set out to review existing methods and establish new methods for recommending borehole abstraction rates in secondary aquifers. The yield assessment methods have been grouped into those that are based on aquifer yield analyses and on the analysis of single borehole test pump data. The aquifer yield methods are based on recharge, storage and throughflow; and the test pump methods are based on different ways of applying the Cooper-Jacob equation (eq.6.10) to the constant discharge test, and on the recovery test that follows the constant discharge test.

In order to assess which methods give suitable yield recommendations, it was necessary to compare the yields obtained using the various methods, to established yields from production boreholes in secondary aquifers. This raised the problems of obtaining data on production boreholes, establishing their maximum sustainable yields, and obtaining the necessary data so that the aquifer yield assessment methods could be applied. With the information provided, it was possible to estimate the likely sustainable yield range of each borehole, rather than their maximum sustainable yields. For this reason, it was only possible to establish which methods gave "acceptable" yields, or those yields which fell within the estimated yield range, and those methods which fell outside each borehole's sustainable yield range. Considering that this study aimed to establish which borehole yield assessment methods are best suited to secondary aquifers, this verification process was acceptable. A limitation of the study is that too few case studies could be found to test the methods based on aquifer yield analyses. The conditions under which these methods can be applied however, were discussed based on the theoretical limitations of each method.

The aim of the aquifer yield assessment methods are to establish an estimate of what a borehole which penetrates a certain aquifer can yield. While methods to determine recharge to an aquifer, the volume of water held in storage and the rate at which water can pass through an aquifer had previously been developed (and were assessed during this study), a method of estimating the proportion of recharge that can be exploited by a single borehole had yet to be developed. This was the focus of the aquifer yield assessment component of the research project.

The method to determine the abstractable proportion of recharge was developed by simulating aquifers with different transmissivities, seepage face widths and different degrees of anisotropy. Various recharge values were used in the computer simulation exercise, and a simple method was developed to estimate the abstractable proportion of recharge. This method proved to be successful when compared to monitored boreholes, so long as: the recharge to the aquifer could be estimated with an acceptable degree of accuracy, since the yield obtained is sensitive to the recharge value and the area contributing to recharge; and the width of the seepage face was not too large, since the method was developed for seepage face widths of up to 3 000 m. In reality this means that the method can only give acceptable results when a borehole falls within a relatively small catchment area, when the depth of the water strikes are relatively shallow, and when the annual recharge can be estimated with a fair degree of accuracy.

In order to obtain a first estimate of annual recharge, recharge values were collated from available quantitative estimates for different regions and geological formations throughout Southern Africa. Several regional estimation methods were presented, and where possible, conservative ones have been proposed which could be used if no suitable local value can be obtained.

The use of aquifer storage and throughflow as the basis on which to determine an estimate of a borehole's potential yield is problematic, because the yields obtained using these methods are sensitive to all the aquifer parameters on which they are based. In the case of using storage, an error margin greater than an order of magnitude could be introduced by the storativity value alone. The concept of using the borehole success rate as a guideline to determine the percentage of sub-surface saturation could be further developed. Likewise, the method proposed to estimate the number of years without recharge, that is, the longest span of years during which annual rainfall is below one standard deviation below the mean rainfall, could also be developed. From an assessment of monitored boreholes, it was found that the storage based method could only be used when the aquifer had been clearly defined in terms of its area, thickness and storativity value. The same applies to the throughflow method - unless a representative transmissivity value for the full width of the aquifer is known, this method can not give acceptable results.

Six methods for estimating the sustainable yield of a borehole based on test pump data were assessed. Two methods were rejected because they could not be applied with any degree of confidence due to their conceptual limitations. They are the maximum drawdown method, and what was described in Chapter 6 as the transmissivity method. Two methods were developed during the course of this study, namely the drawdown-to-boundary and distance-to-boundary methods, and both are based on the Cooper-Jacob approximation of the Theis equation.

The recovery method, which is based on the time it takes for the water level in a borehole to return to the original rest water level after the constant discharge test, was found to be unreliable for the purpose of establishing a borehole's suitable long term abstraction rate. Curve extrapolation (to obtain a t/t' value) is usually required, and this frequently produces non-unique values or values which result in a negative yield recommendation. The conceptual basis of the method was also questioned, with the suggestion that the recovery time may not necessarily be dependant on the preceding pumping rate. It is proposed that the application of this method be restricted to tests where the pumping rate is close to the borehole's capacity and where the recovery is complete. Even under these conditions however, the method may not give suitable results. Rapid recovery can occur as a result of leakage from overlying material or variations in storativity. The relatively high t/t' values which could be obtained would result in the calculation of large yield values which may not be sustainable, since the extent of storage in these horizons is not taken into account.

Although the recovery method proved to be unreliable, the recovery curve proved to be useful in establishing whether a conservative yield obtained from the other yield assessment methods should be recommended. A recovery period which extends beyond the duration of the constant discharge test or incomplete recovery, indicates that the aquifer is of a limited extent or that it consists of lower permeability boundaries, and that a conservative yield recommendation may be necessary.

In highly permeable fractured rock aquifers with limited storage and recharge, the late-T method has potential to greatly overestimate a borehole's sustainable yield, since it assumes that aquifer permeability is the factor which limits the borehole's sustainable yield. In the examples used, the available drawdown value, as determined by the distance between the rest water level and the depth of the borehole's main water strike, proved to be too high. From this assessment, the method could be used in cases where shallow water strikes are encountered and where the late-time transmissivity values are not very high. If such conditions are not present, the first water strike rather than the main water strike could be used in order to obtain a more conservative yield recommendation.

The drawdown-to-boundary method proved to be the most reliable method out of those which are based on test pump data analysis. The method relies on establishing a suitable available drawdown, which for most of the cases studied, could be taken as the inflection point from the early-time to the late-time slope on the drawdown curve. Where incomplete recovery is experienced after the constant discharge test, or in cases where the thickness of the main aquifer that supports the borehole (commonly the saturated weathered zone) is limited, it may be preferable to use this thickness as the available drawdown in order to recommend a more conservative yield.

The distance-to-boundary method may also be of great value in situations where the limited extent of the aquifer, or heterogenous aquifer permeability, prove to be the factor limiting sustainable yield. This method gave acceptable results in most of the cases studied, but should only be applied when the drawdown curve shows double porosity or boundary effects. Under these circumstances a reasonable Δh value can often be obtained, which for Karoo aquifers, seems to be no greater than 1m.

In order to recommend a yield for a single borehole which is likely to be sustainable, it is necessary to first determine which out of recharge, storage or aquifer permeability are likely to be the limiting factors. While the recharge method should give a good indication of a borehole's potential yield in small catchments where recharge can be accurately estimated, the appropriate borehole yield method should be used to calculate an optimal yield based on permeability or boundary limitations.

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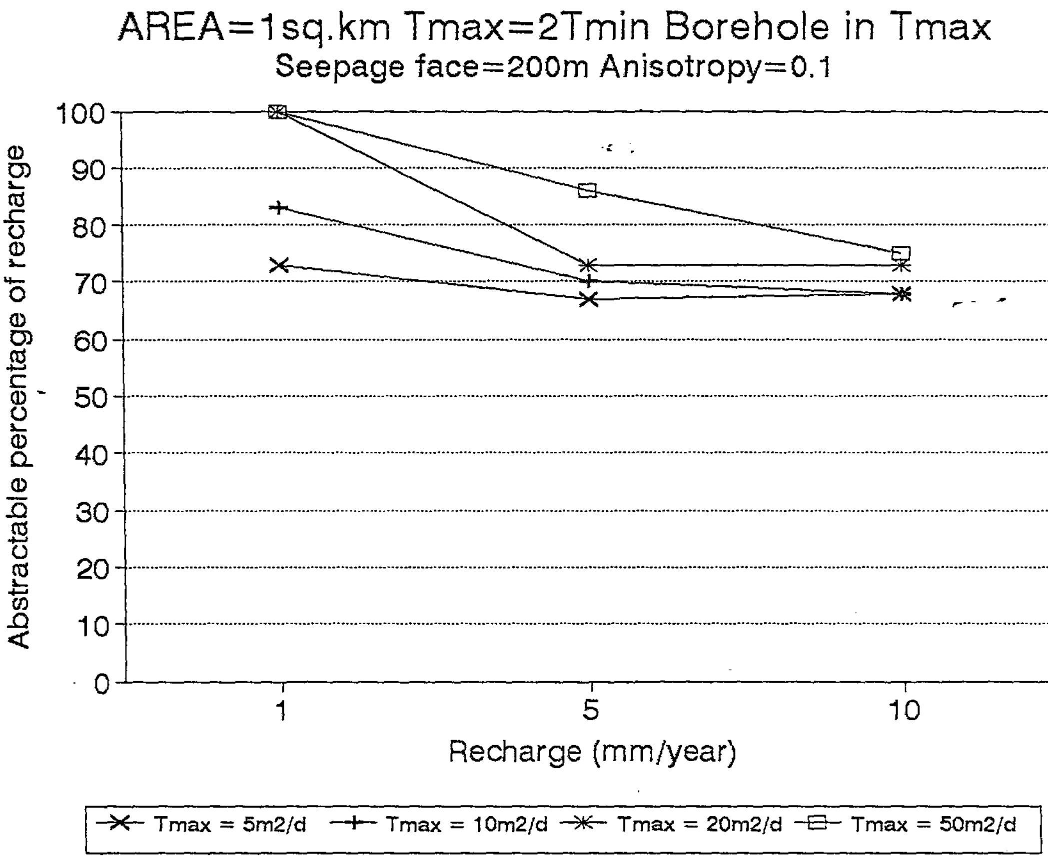
APPENDIX 1

ABSTRACTABLE PROPORTION OF RECHARGE:

RESULTS OF THE MODELLING STUDY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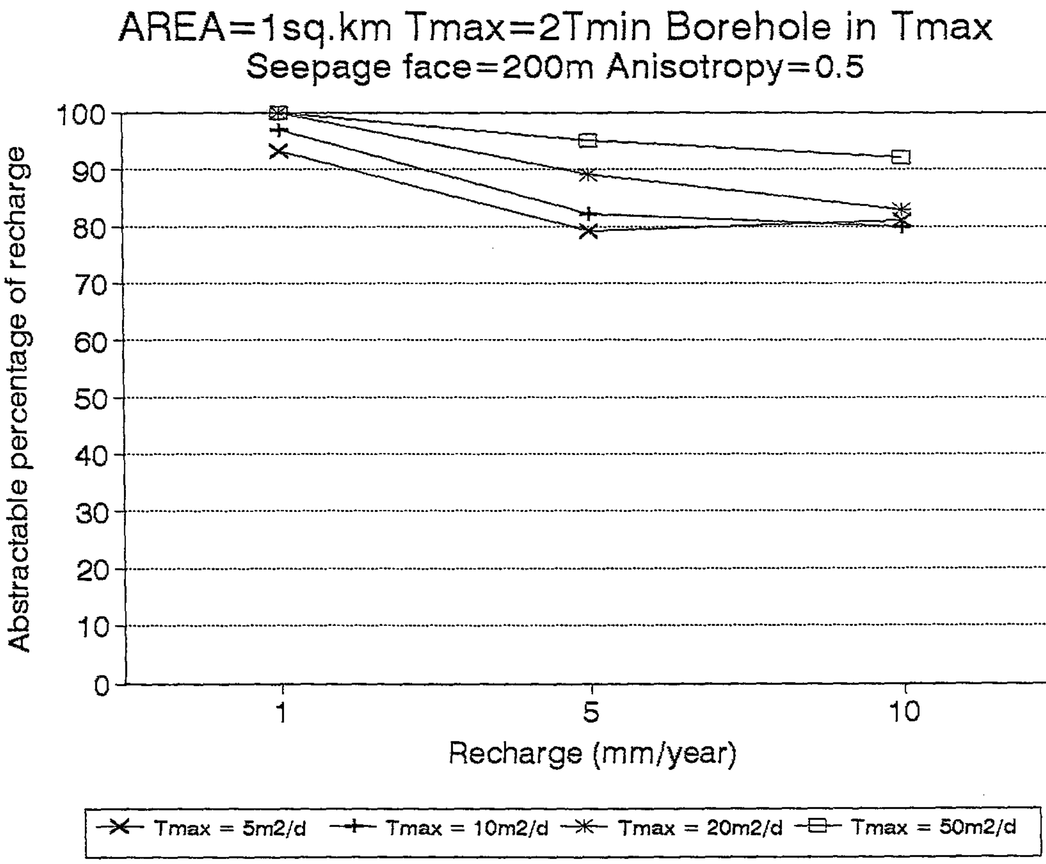
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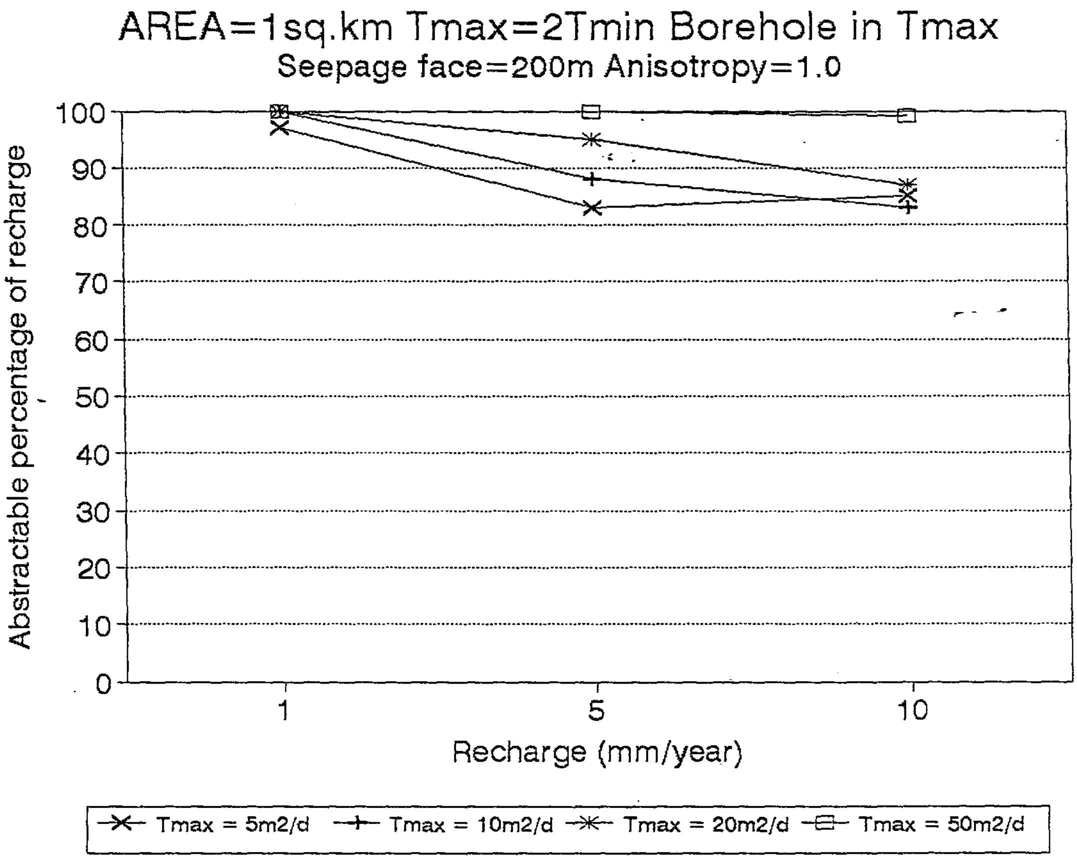

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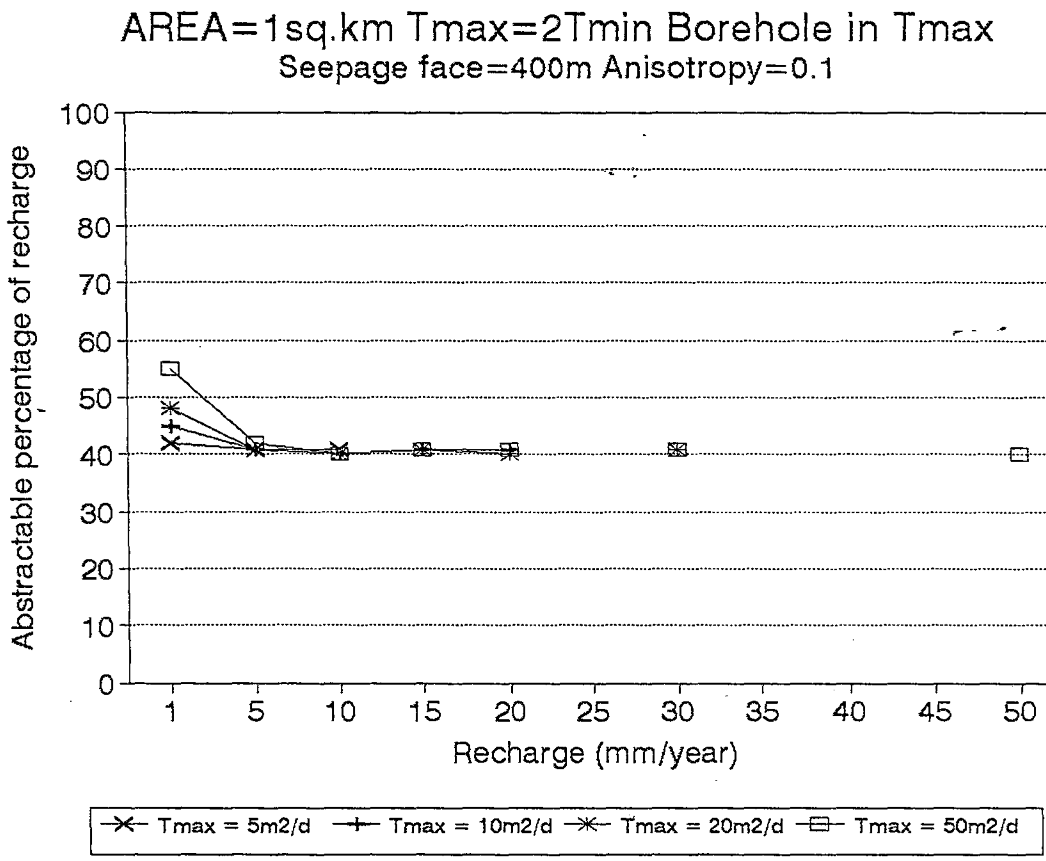
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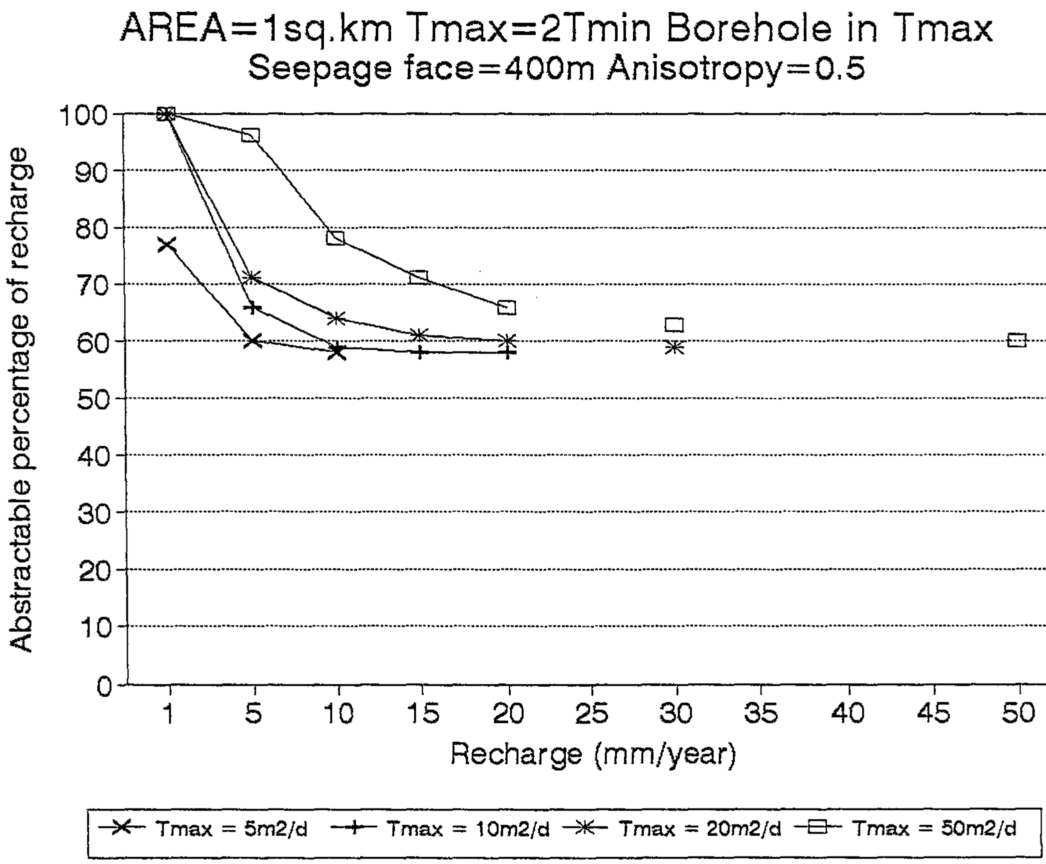
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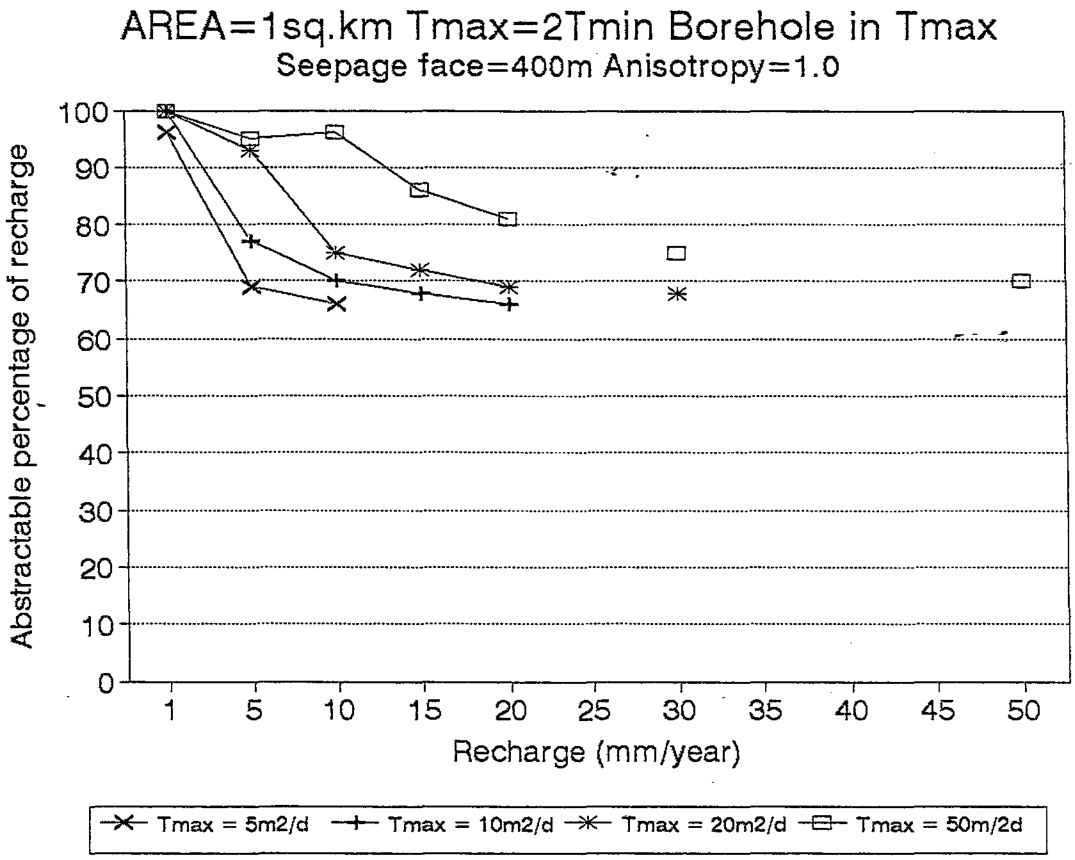

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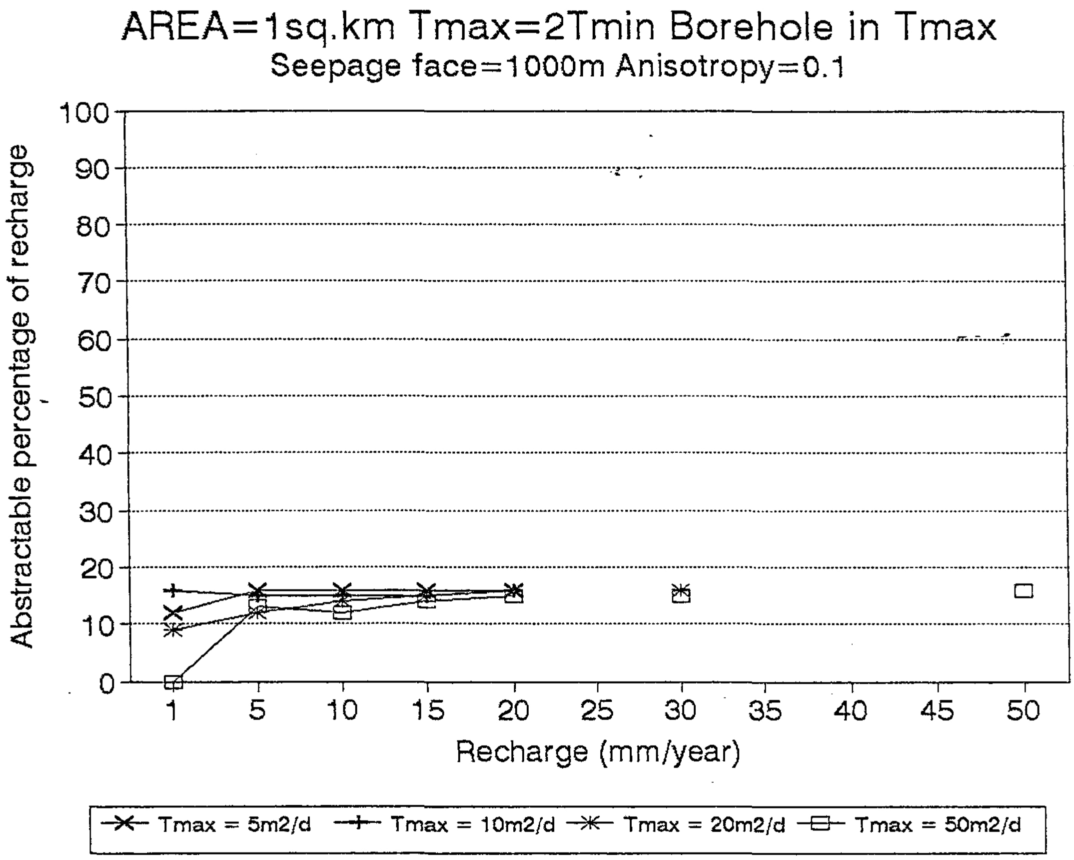
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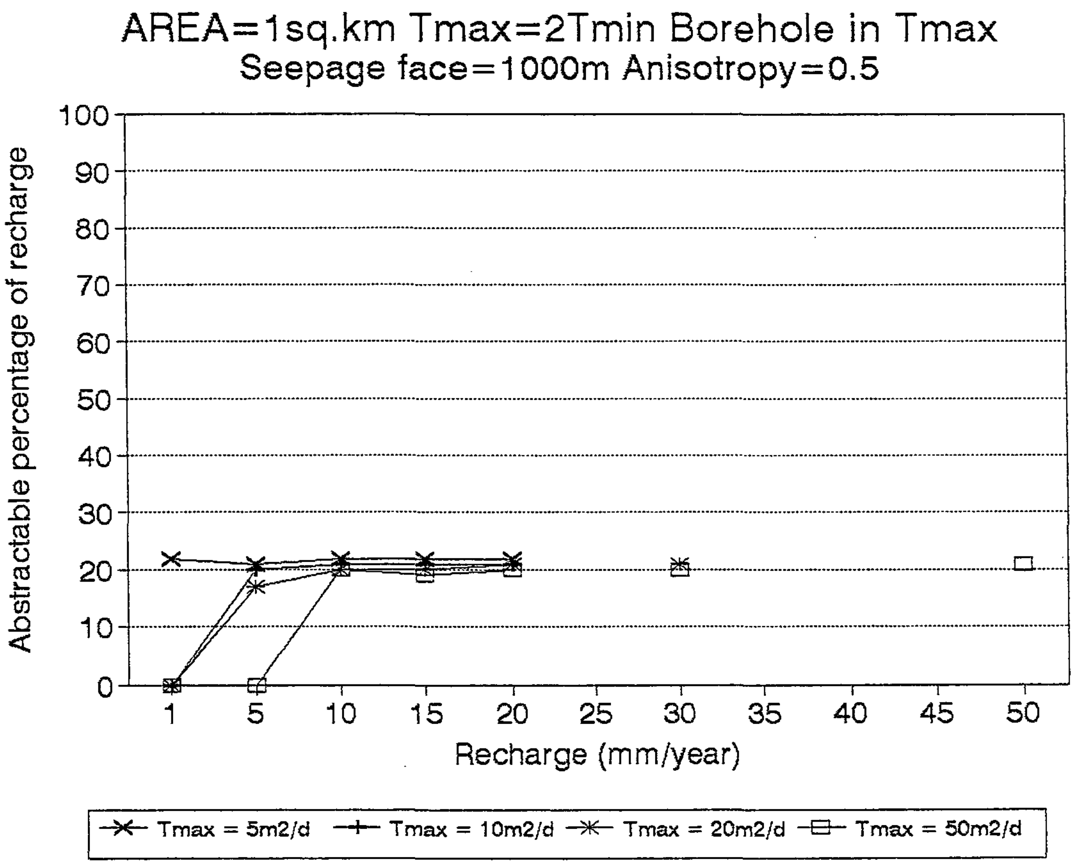
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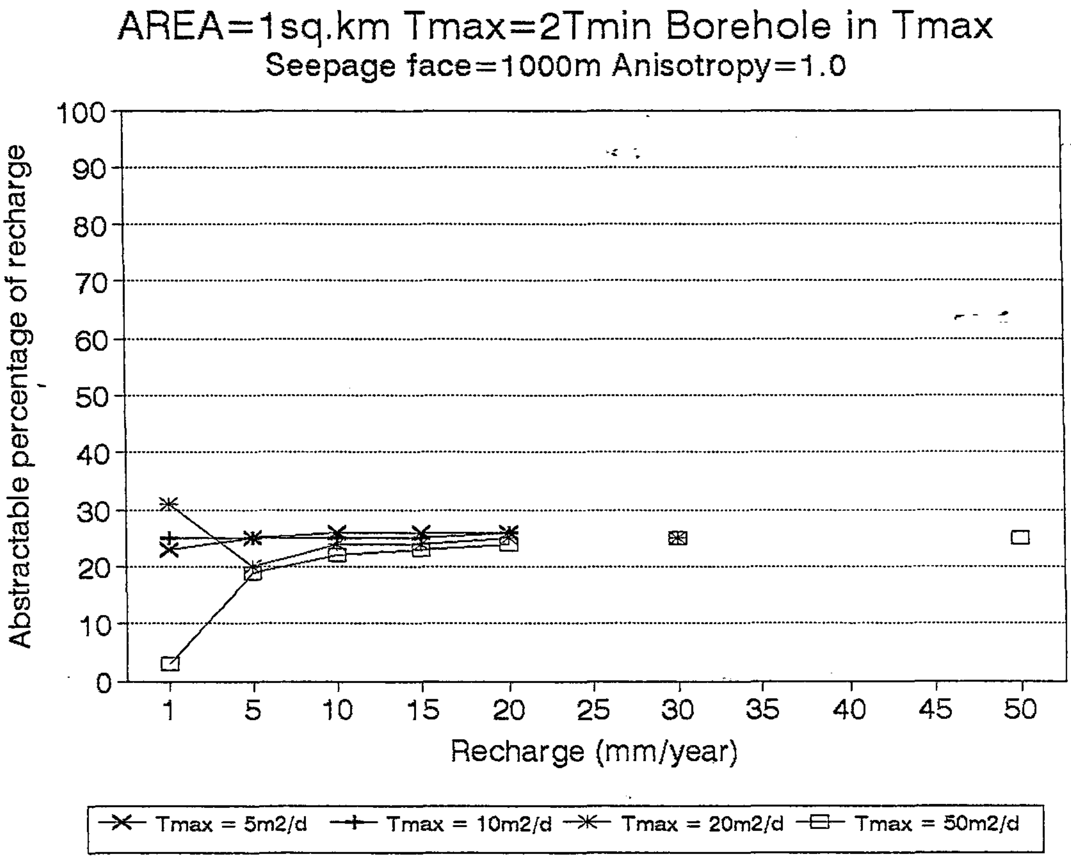

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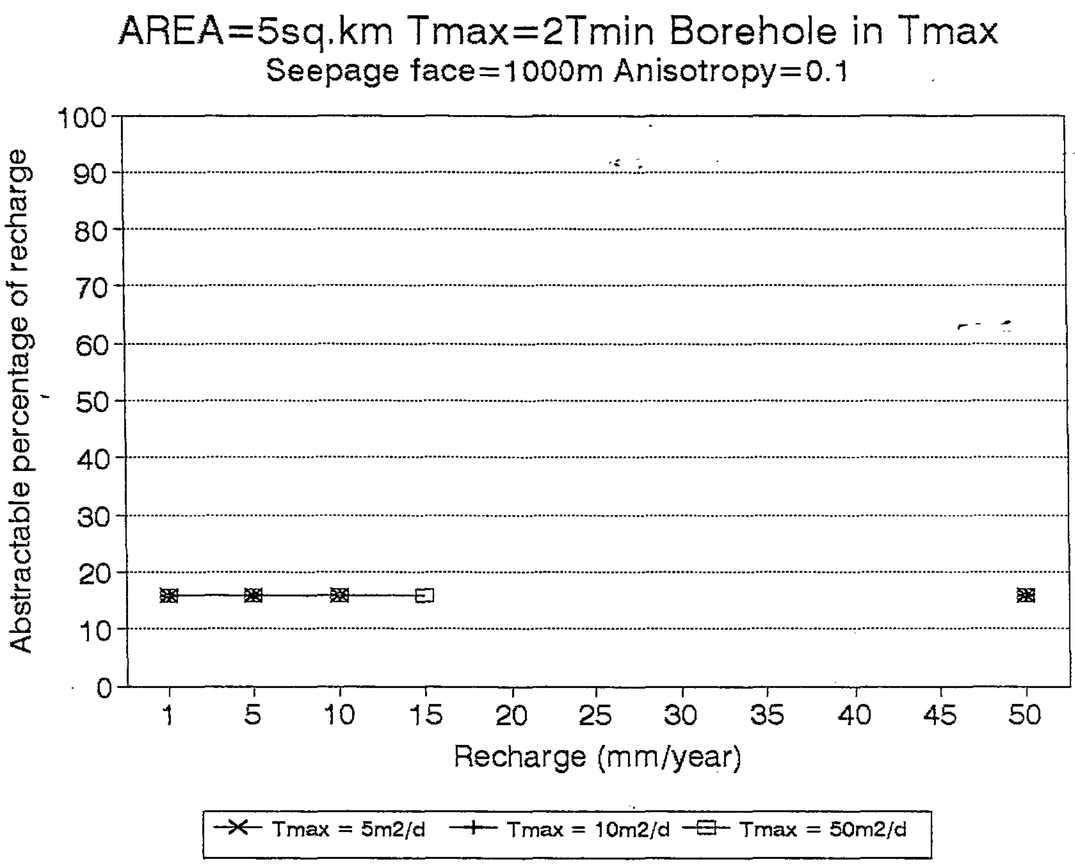
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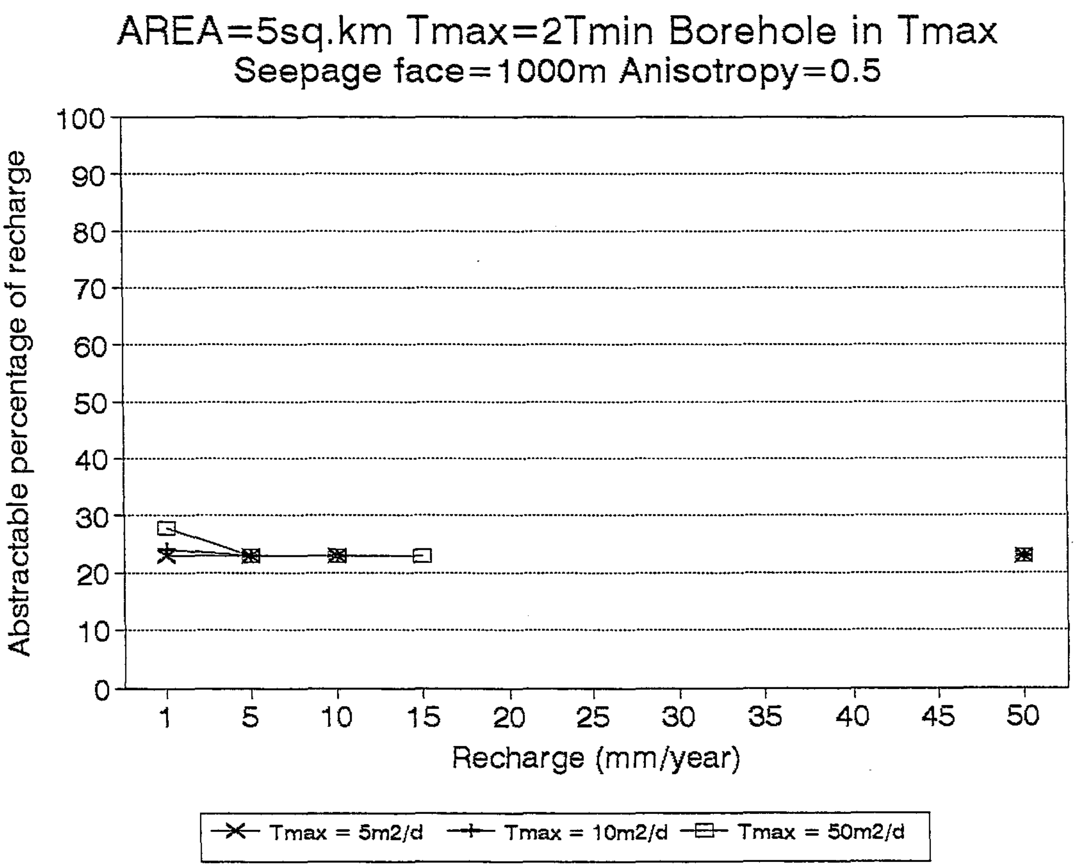
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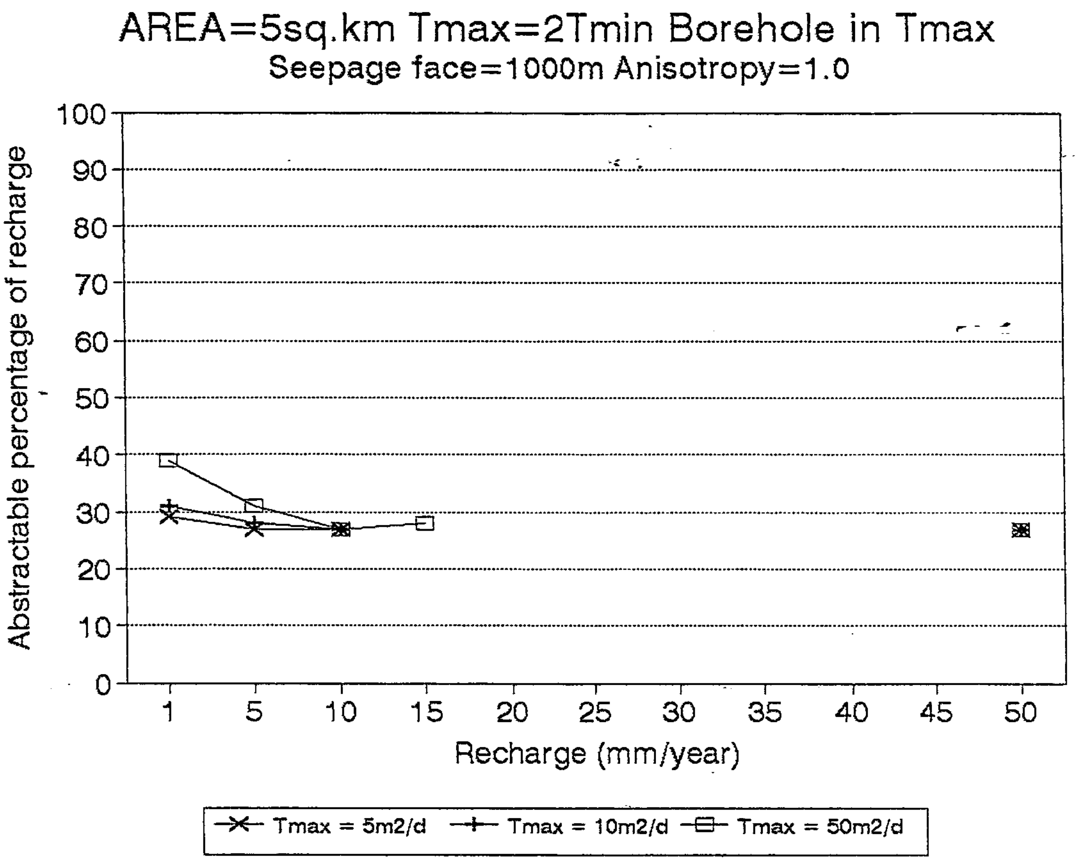
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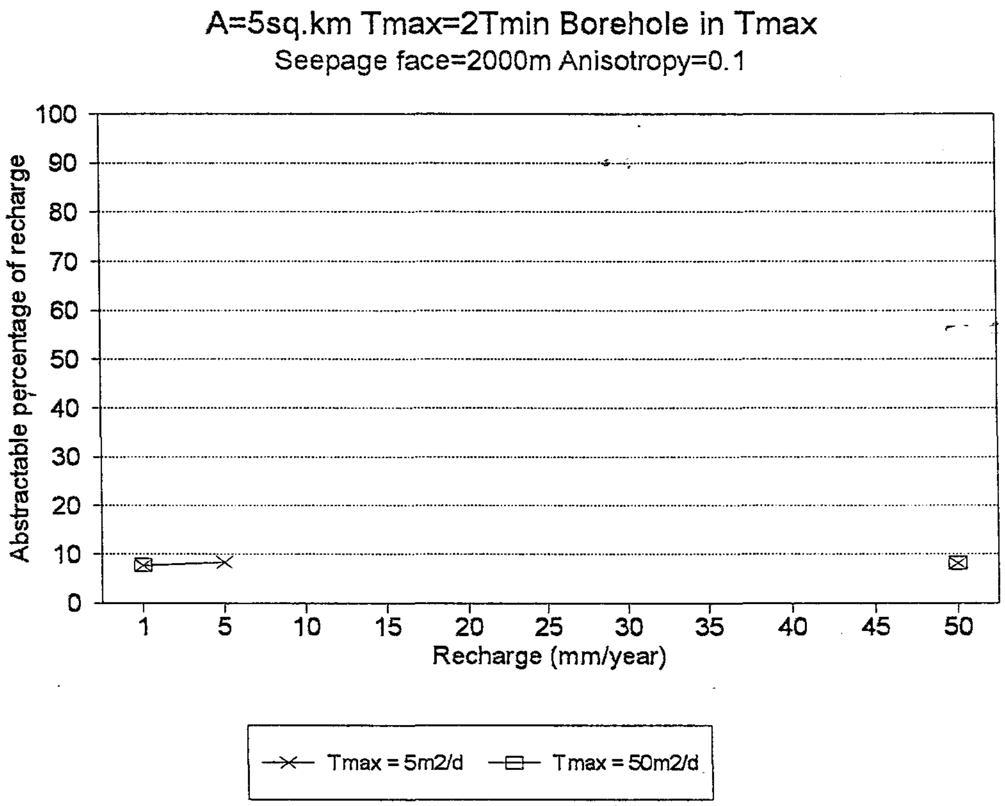
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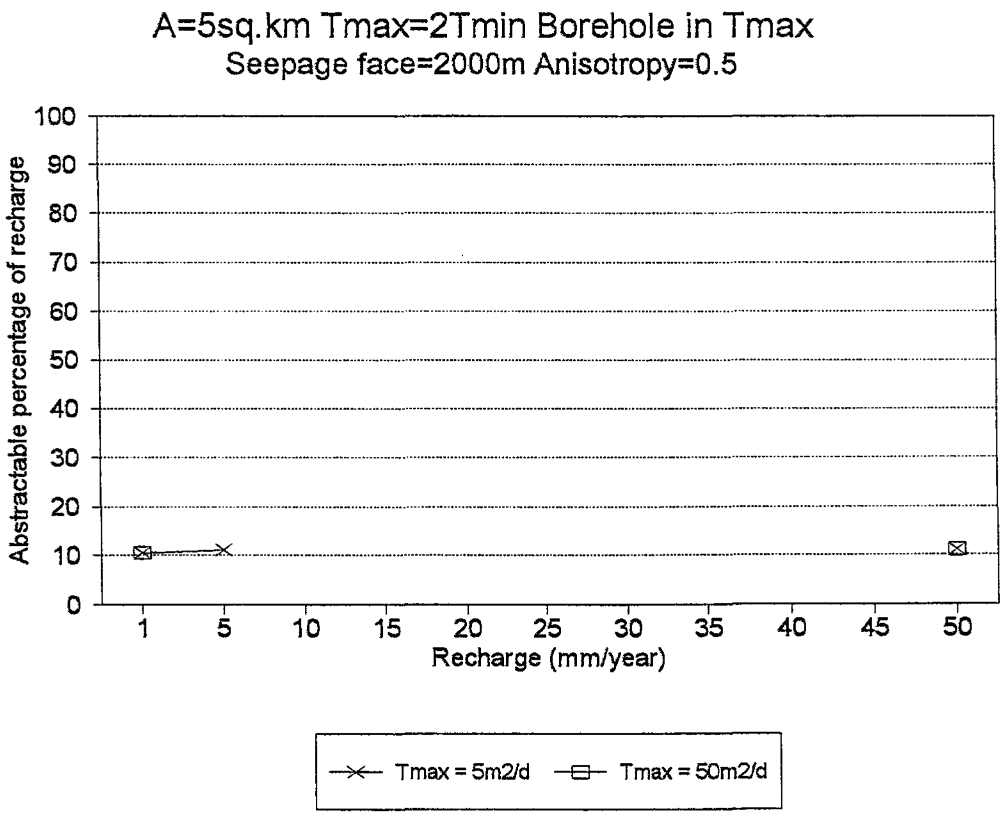
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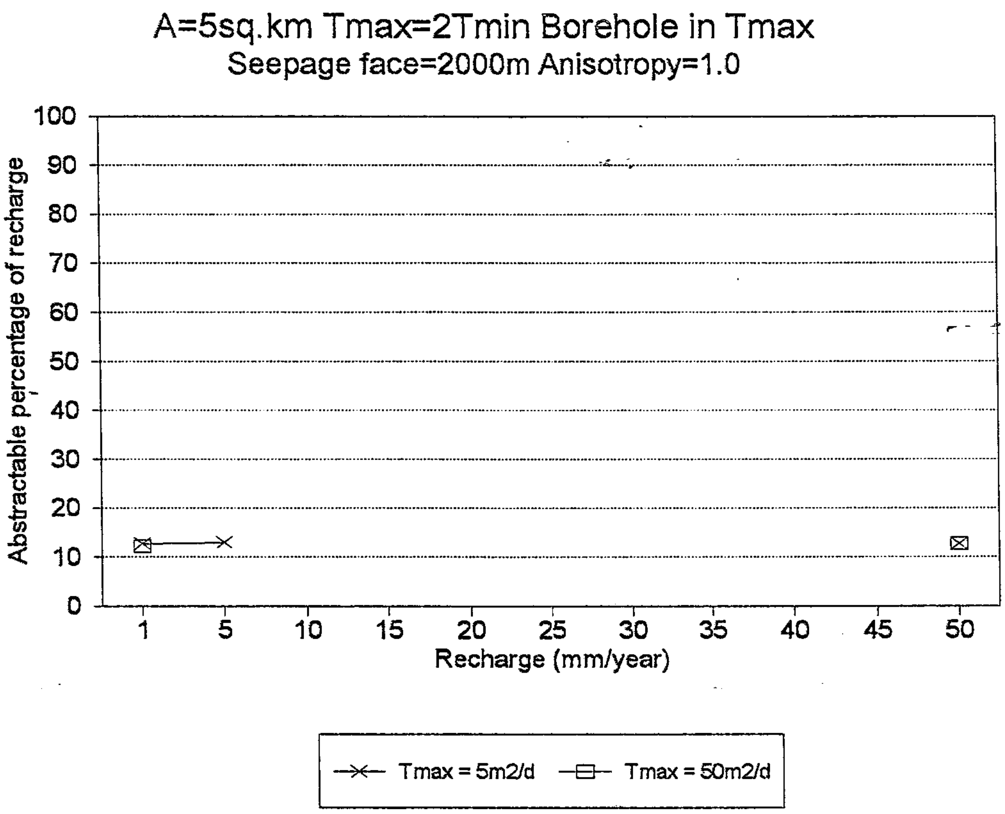
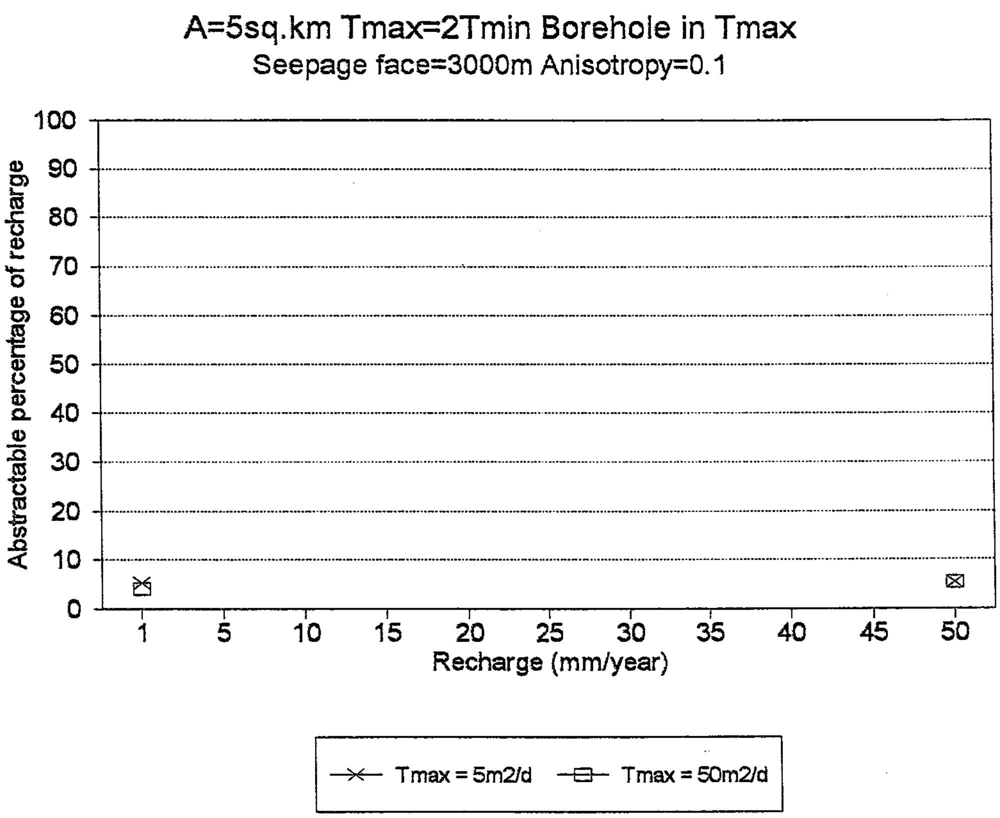
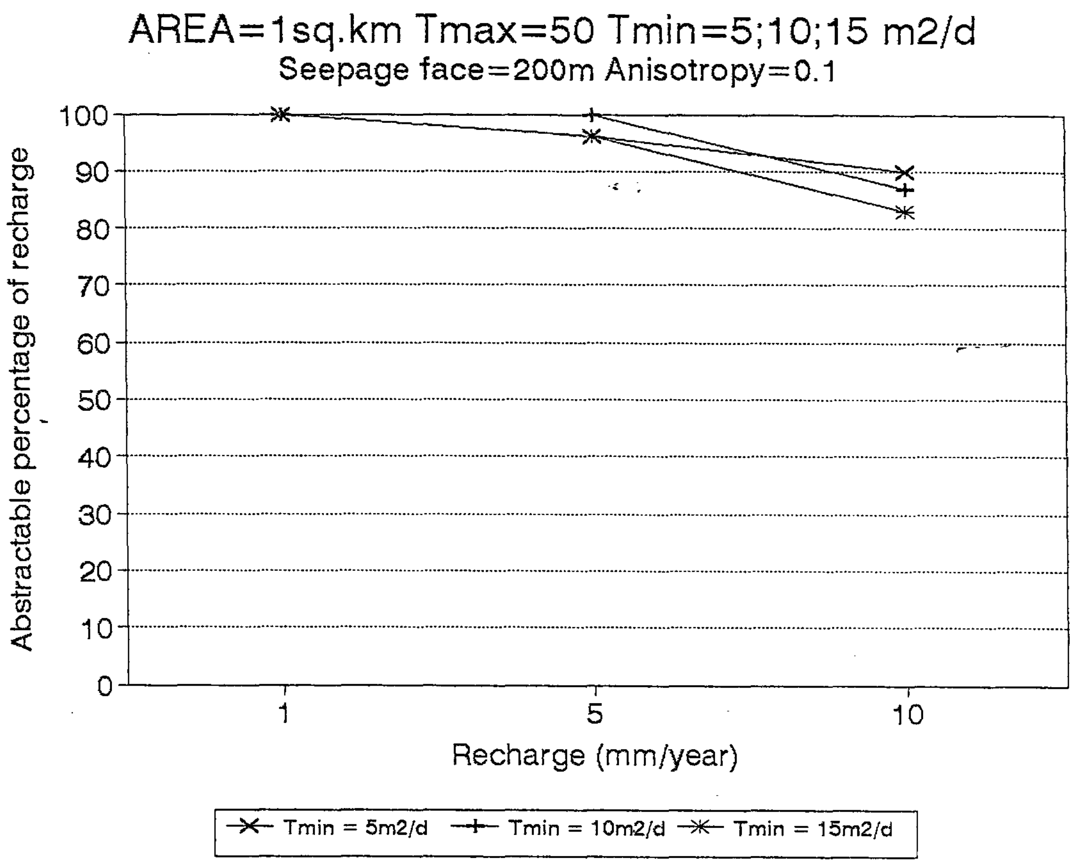
Tmax = 5m2/d
Tmax = 50m2/d

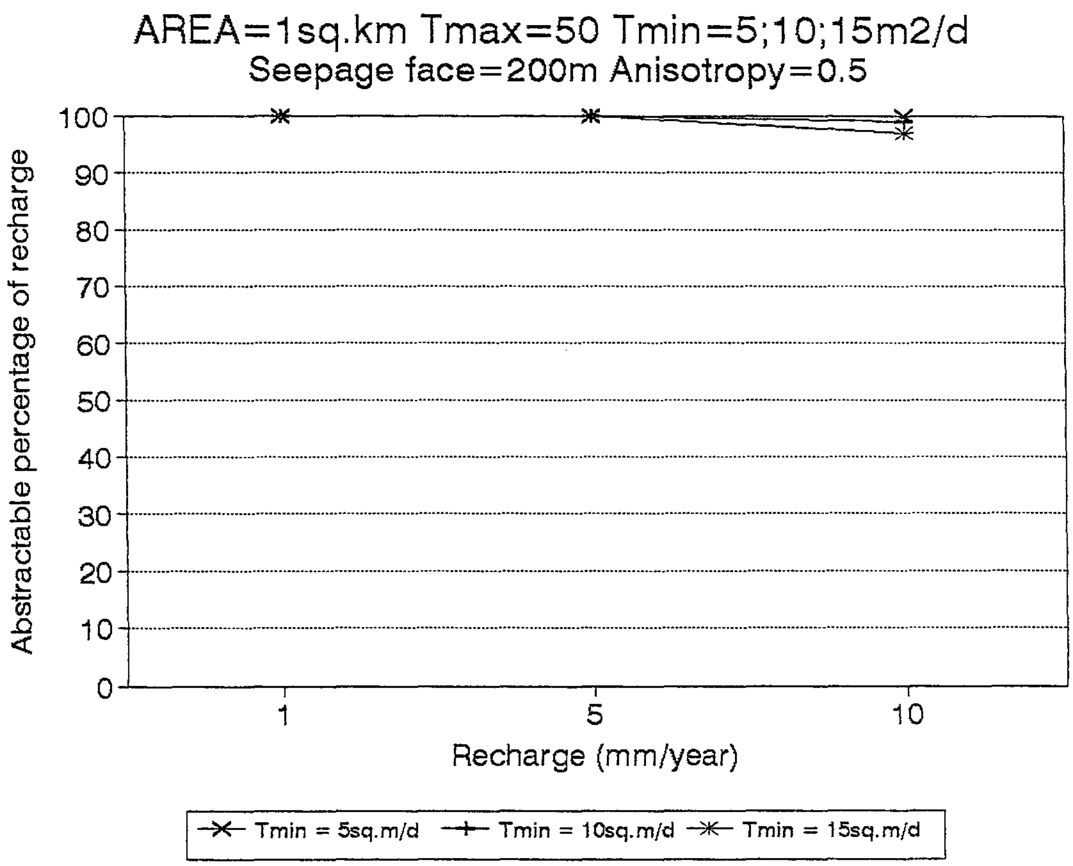


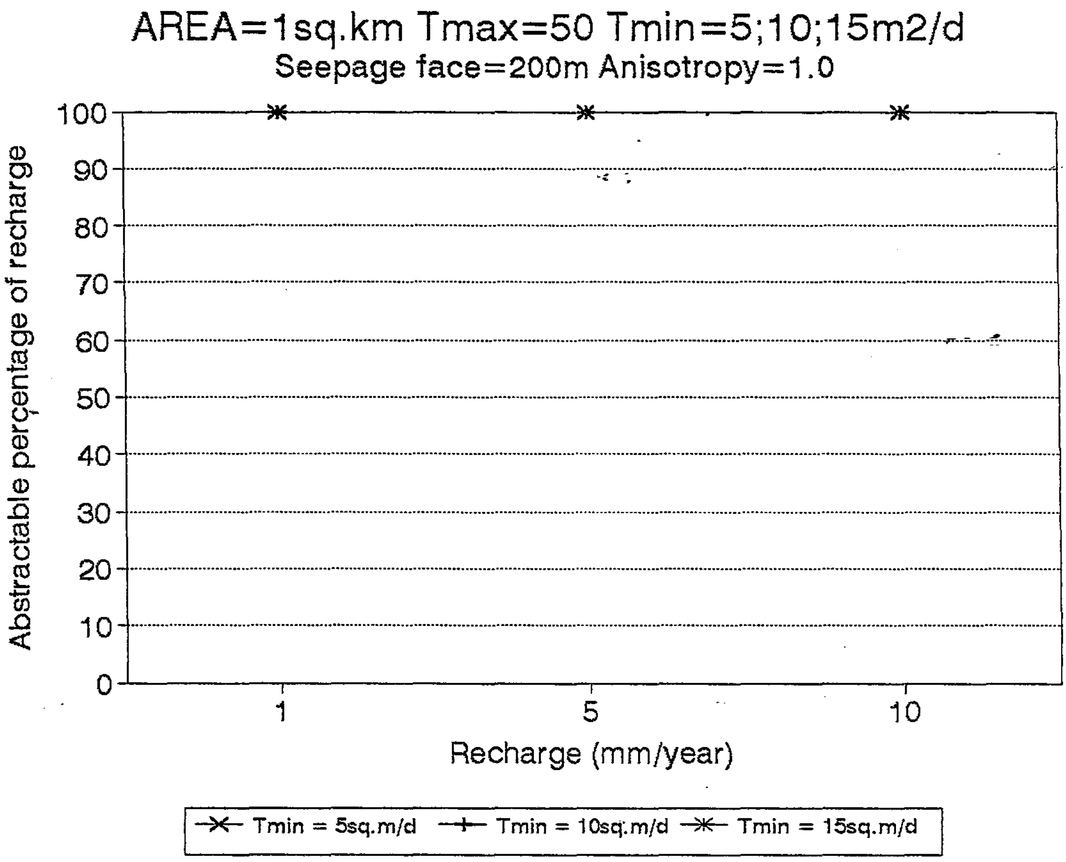
A=5sq.km Tmax=2Tmin Borehole in Tmax
Seepage face=2000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d

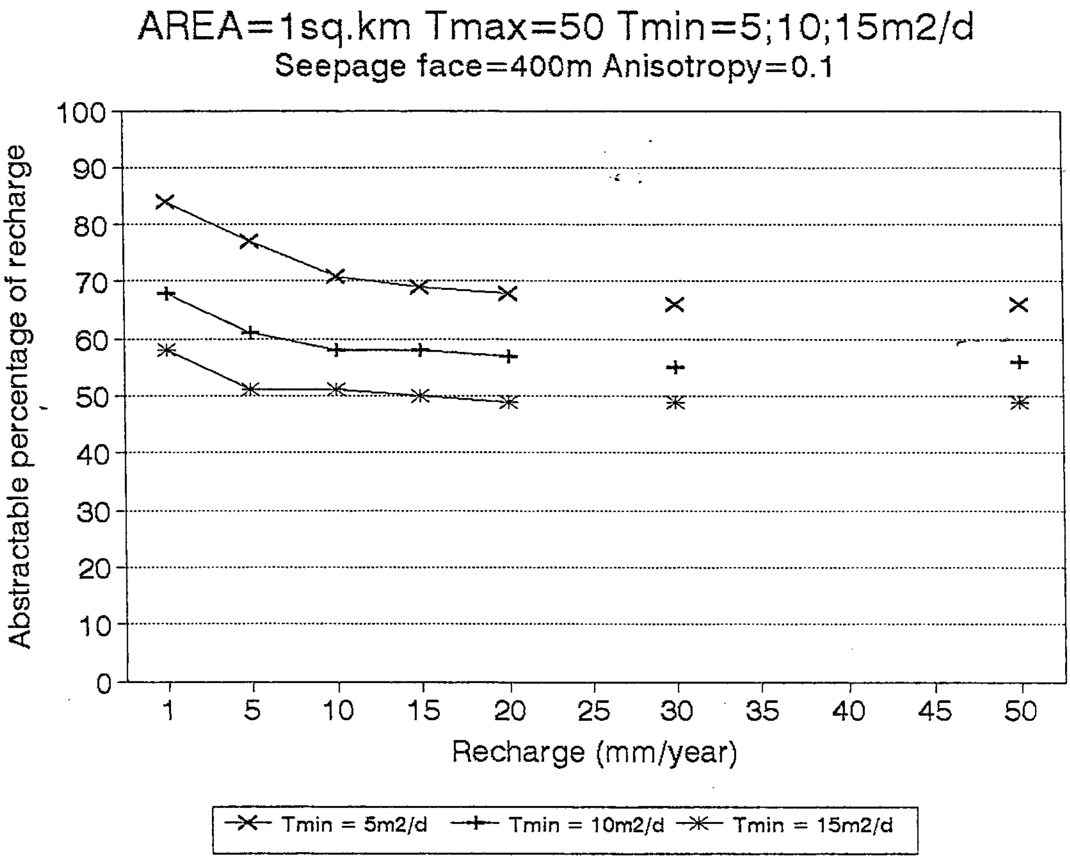


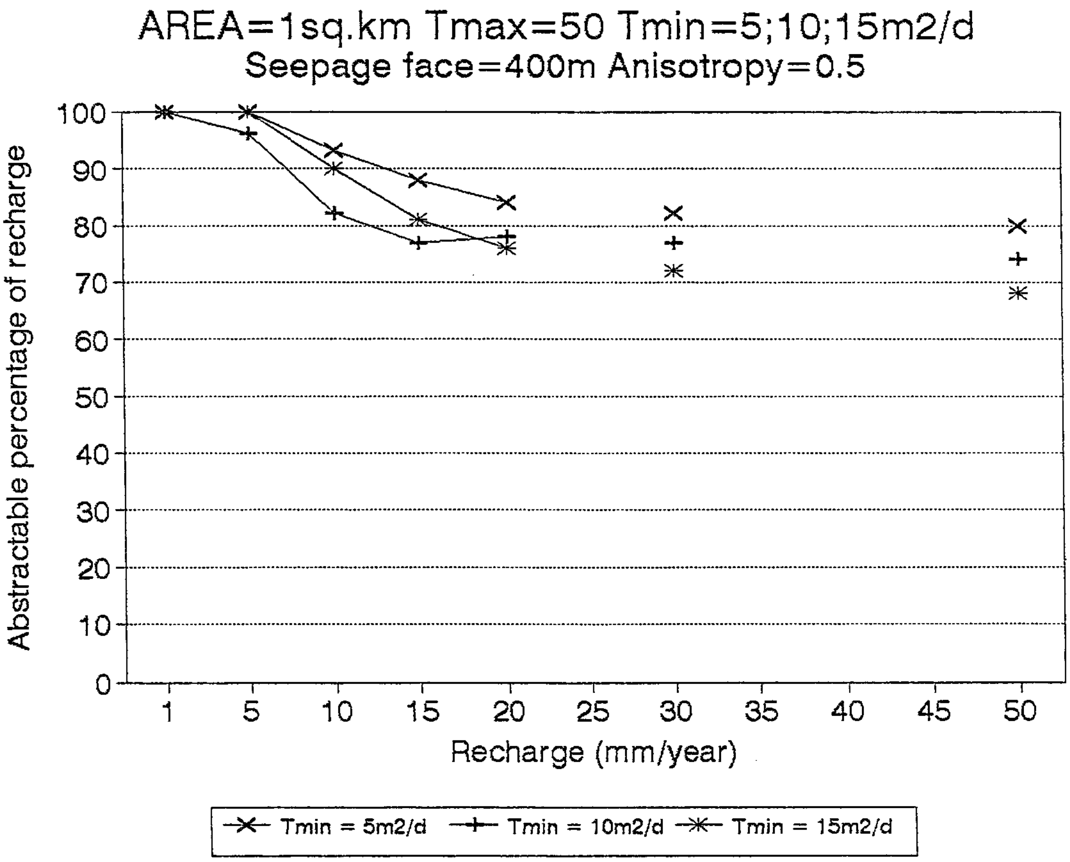
A=5sq.km Tmax=2Tmin Borehole in Tmax
Seepage face=3000m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d

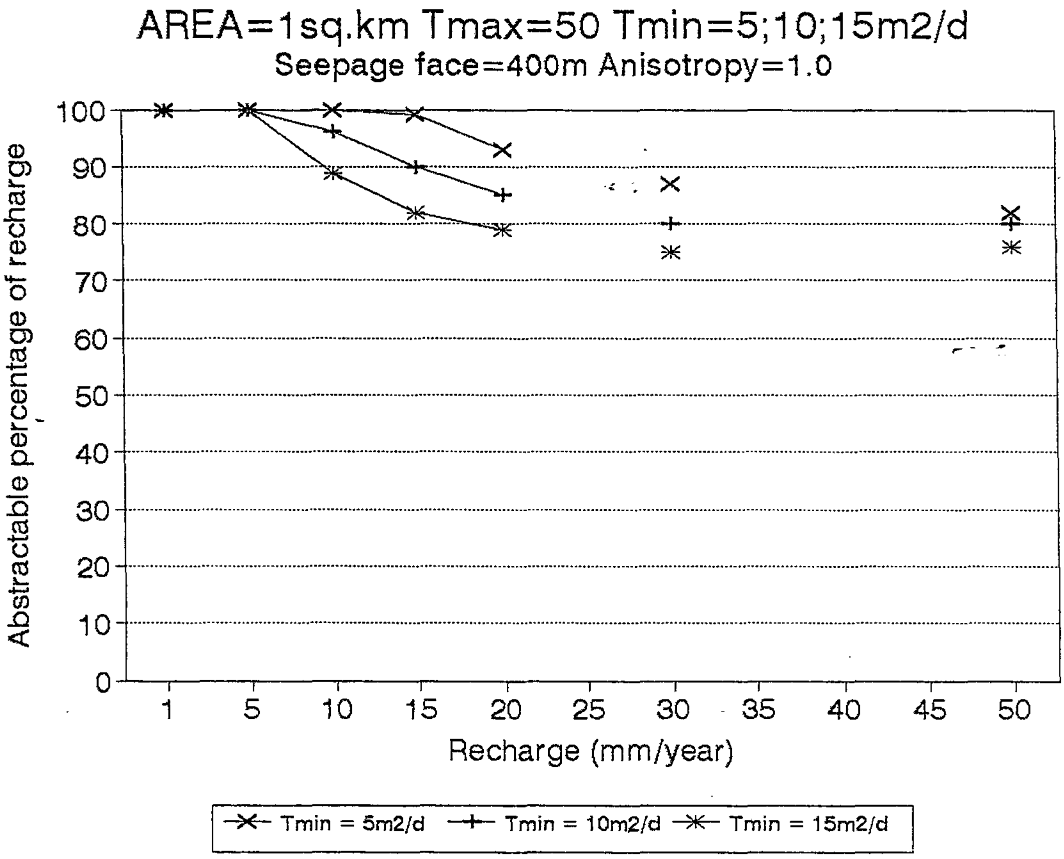

AREA=1sq.km Tmax=50 Tmin=5;10;15 m2/d
Seepage face=200m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d

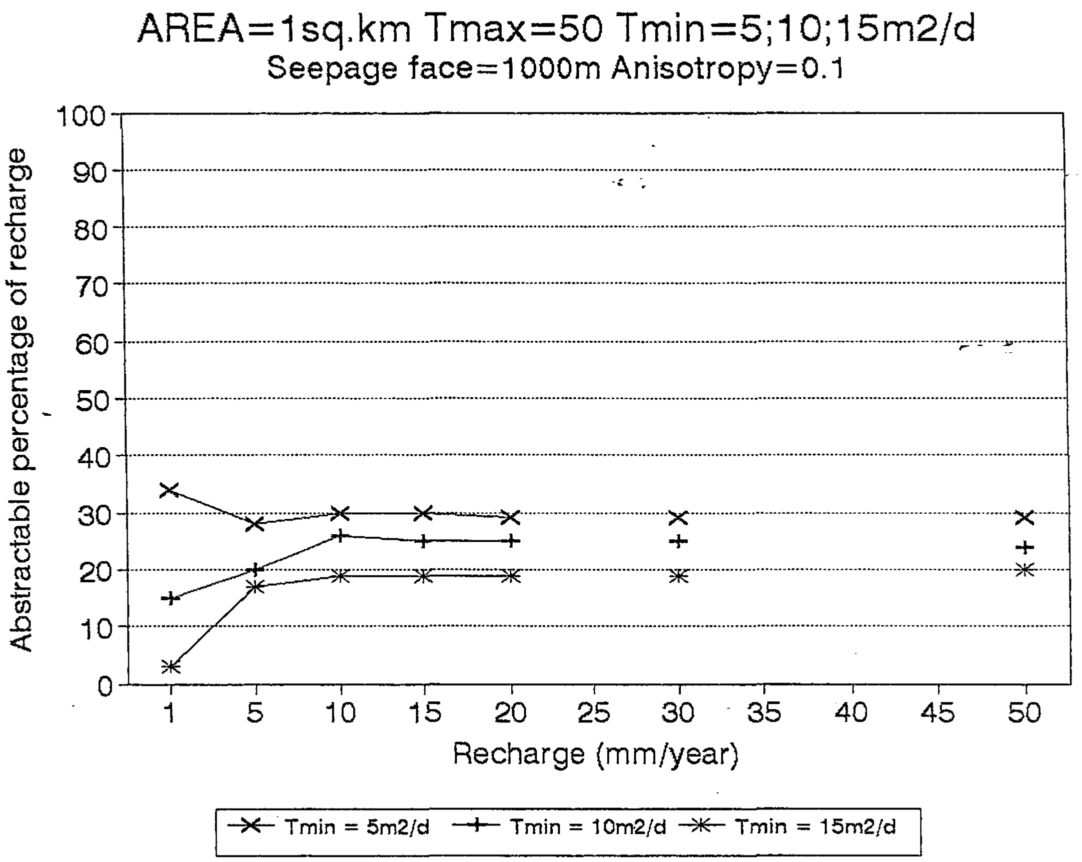

AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=200m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
Recharge (mm/year)
Tmin = 5sq.m/d
Tmin = 10sq.m/d
Tmin = 15sq.m/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=200m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
Recharge (mm/year)
Tmin = 5sq.m/d
Tmin = 10sq.m/d
Tmin = 15sq.m/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=400m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=400m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=400m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
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10
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25
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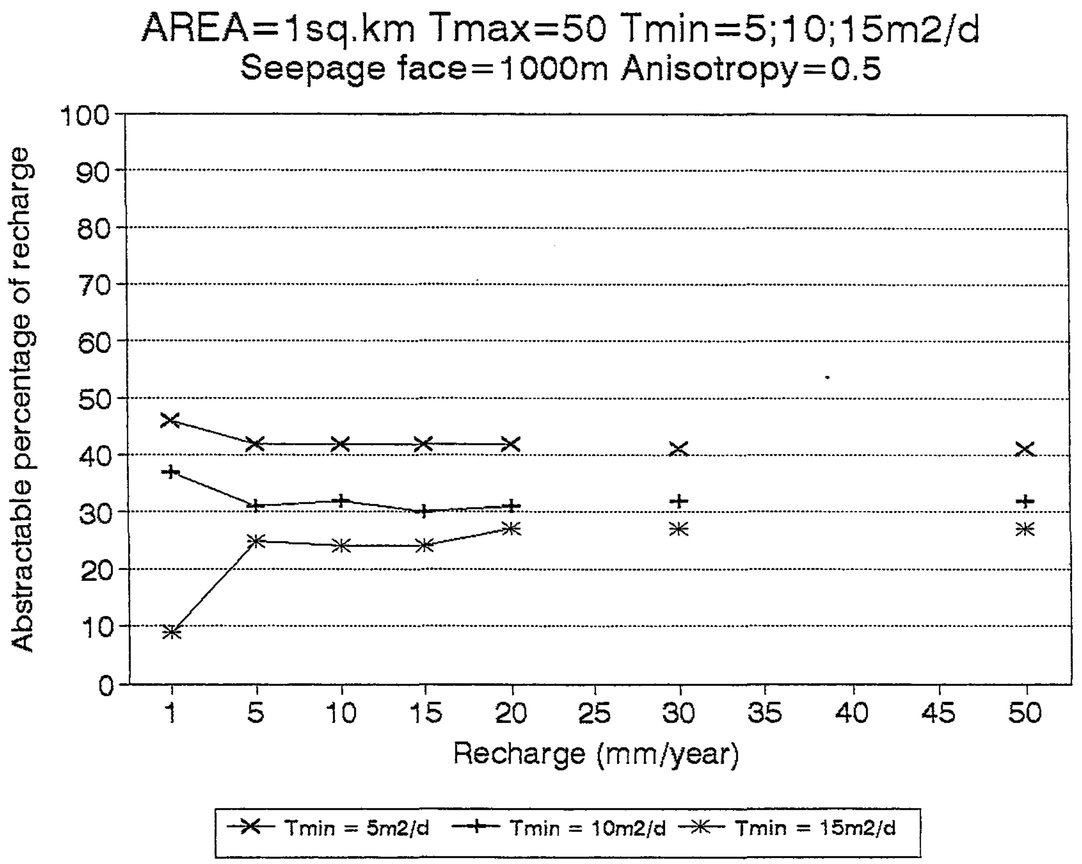
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
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10
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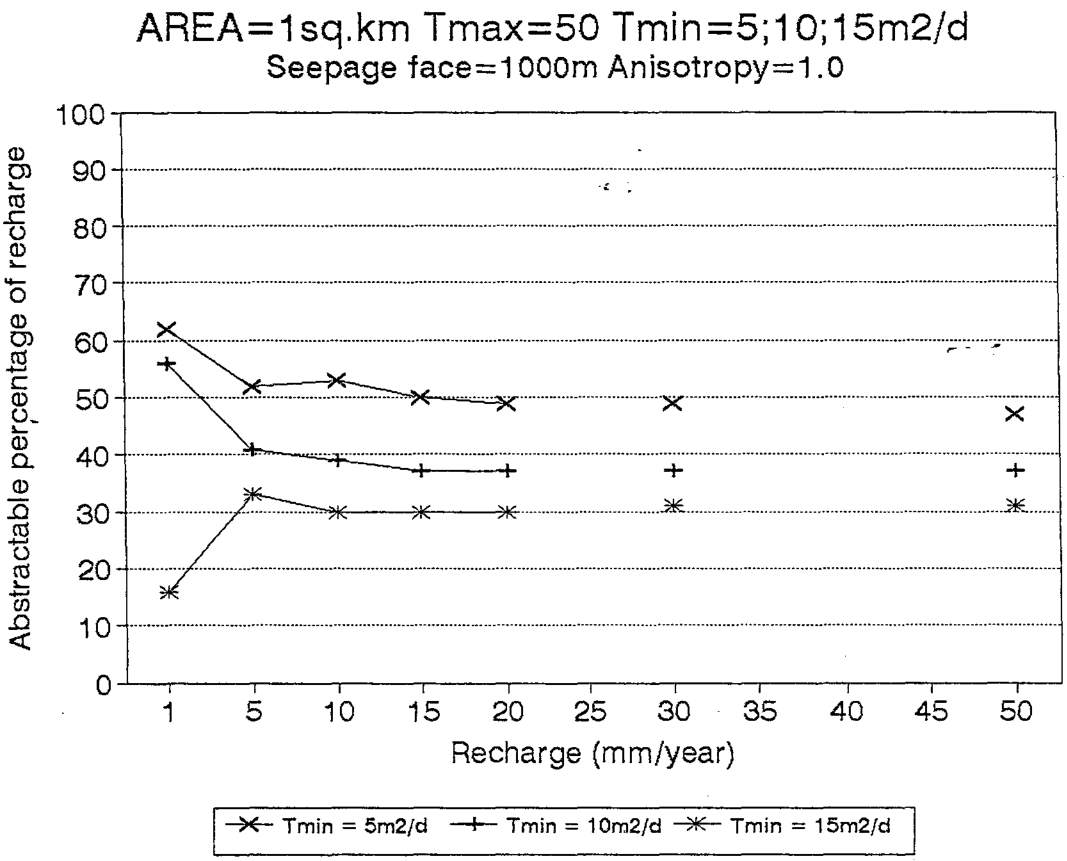
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d



AREA=1sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
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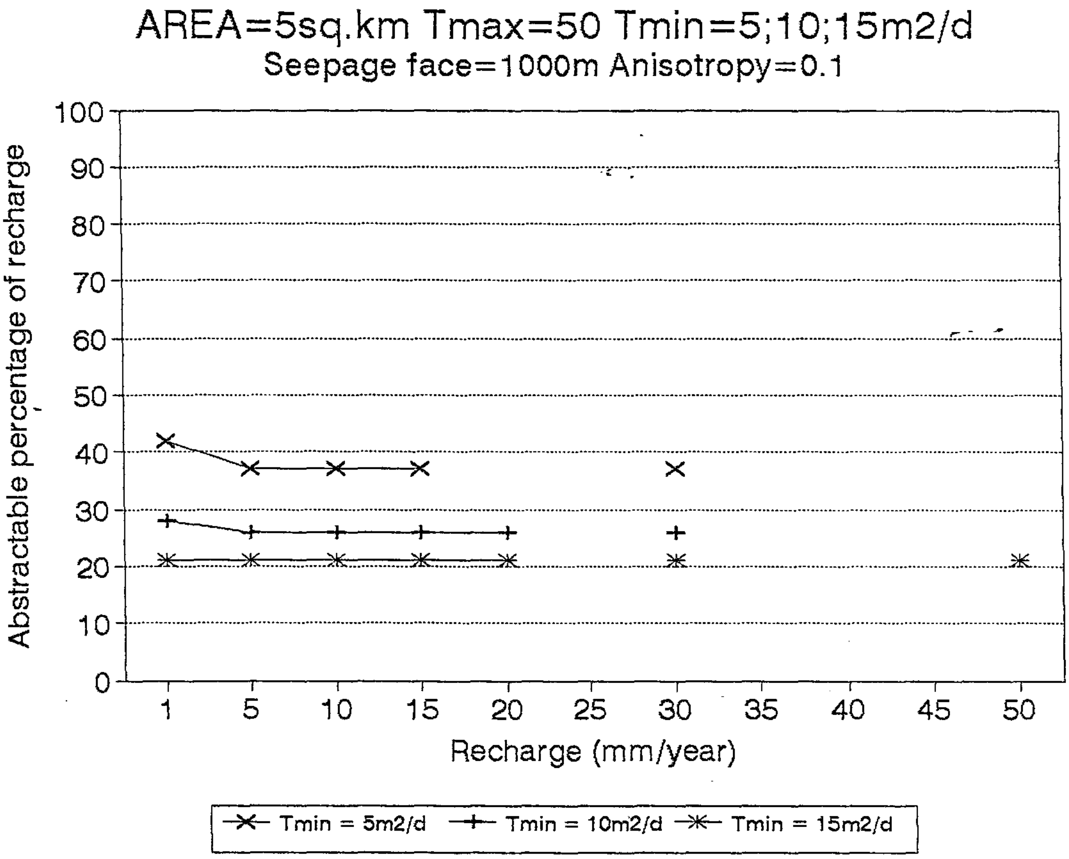
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=5sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
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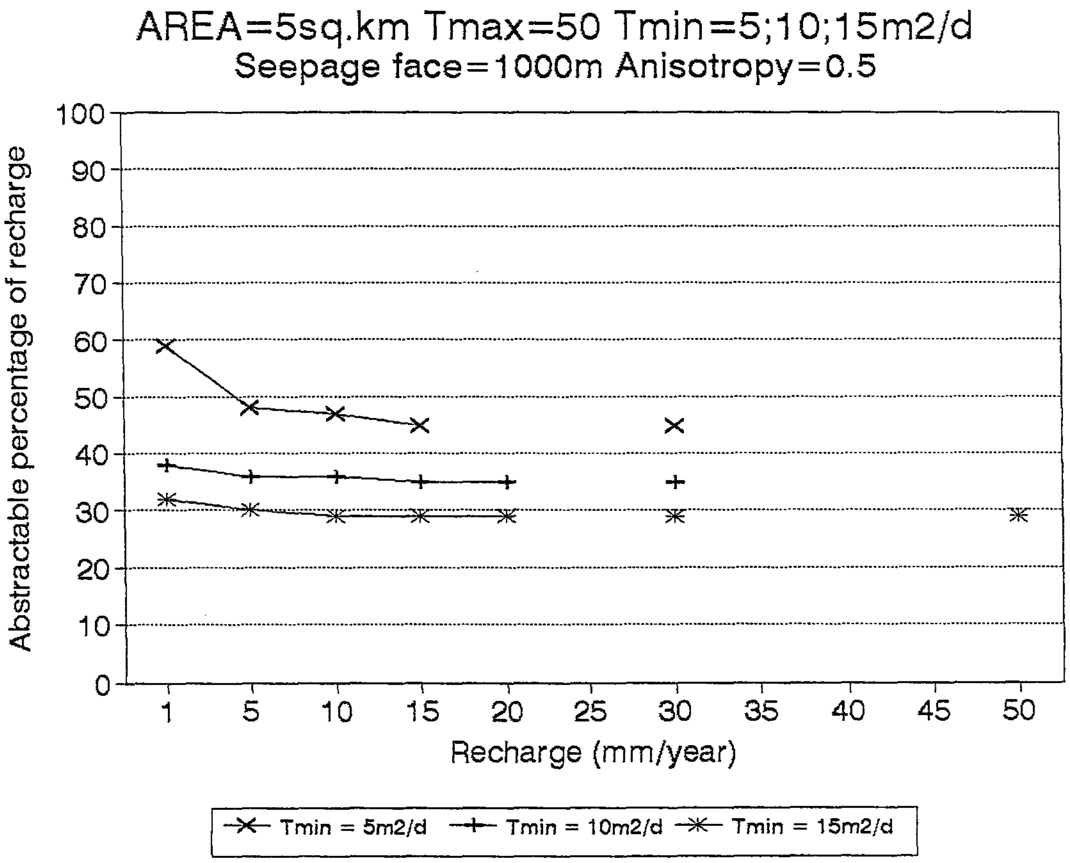
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=5sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
100
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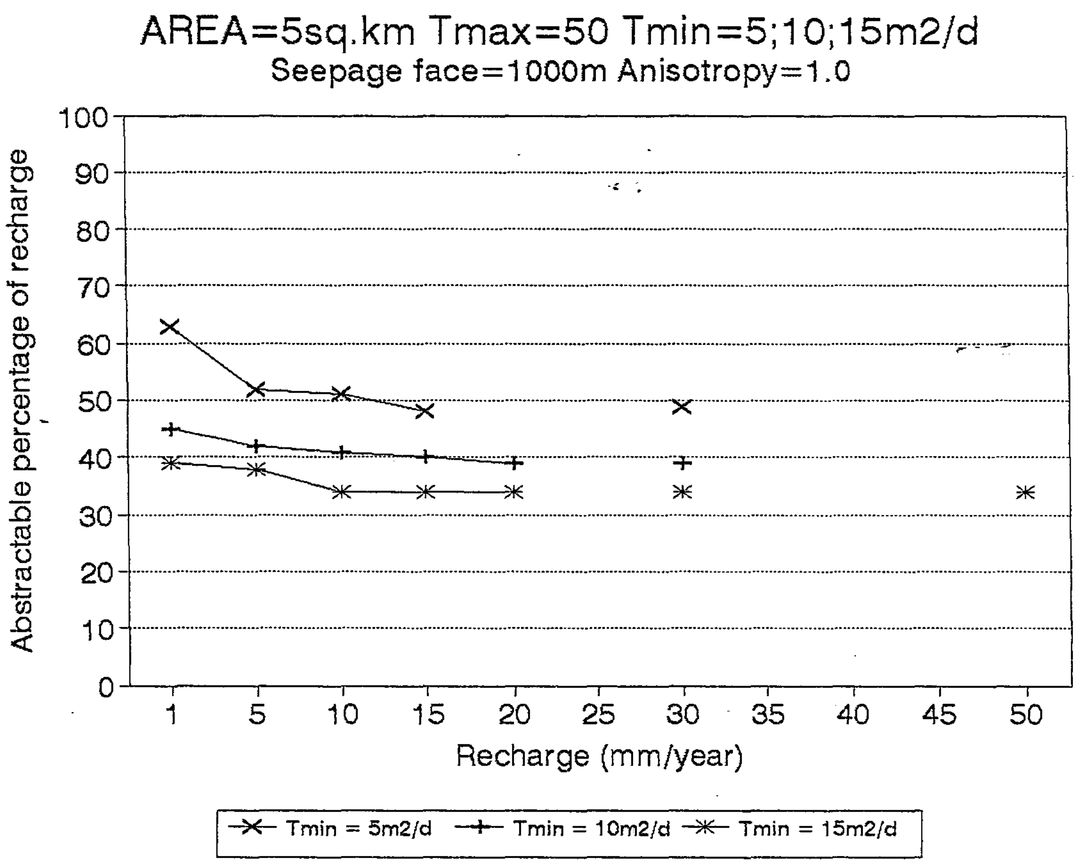
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=5sq.km Tmax=50 Tmin=5;10;15m2/d
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
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90
80
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50
40
30
20
10
0
1
5
10
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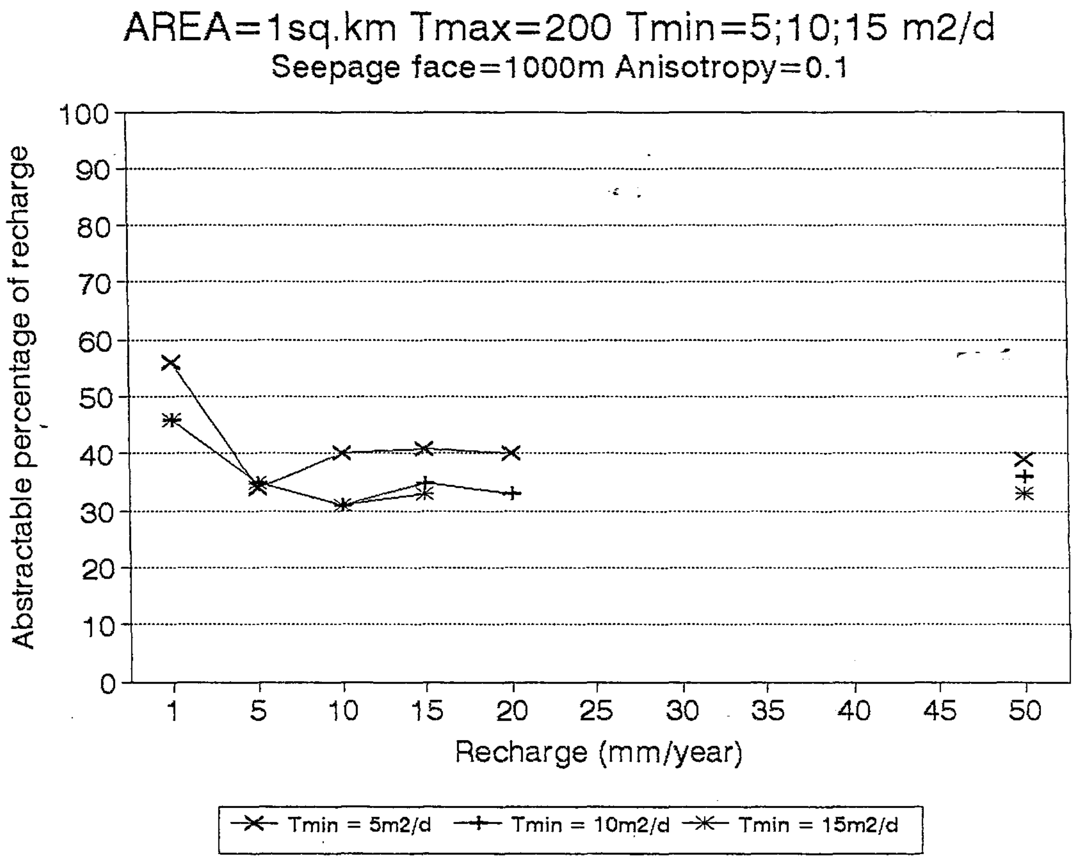
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d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Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
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80
70
60
50
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20
10
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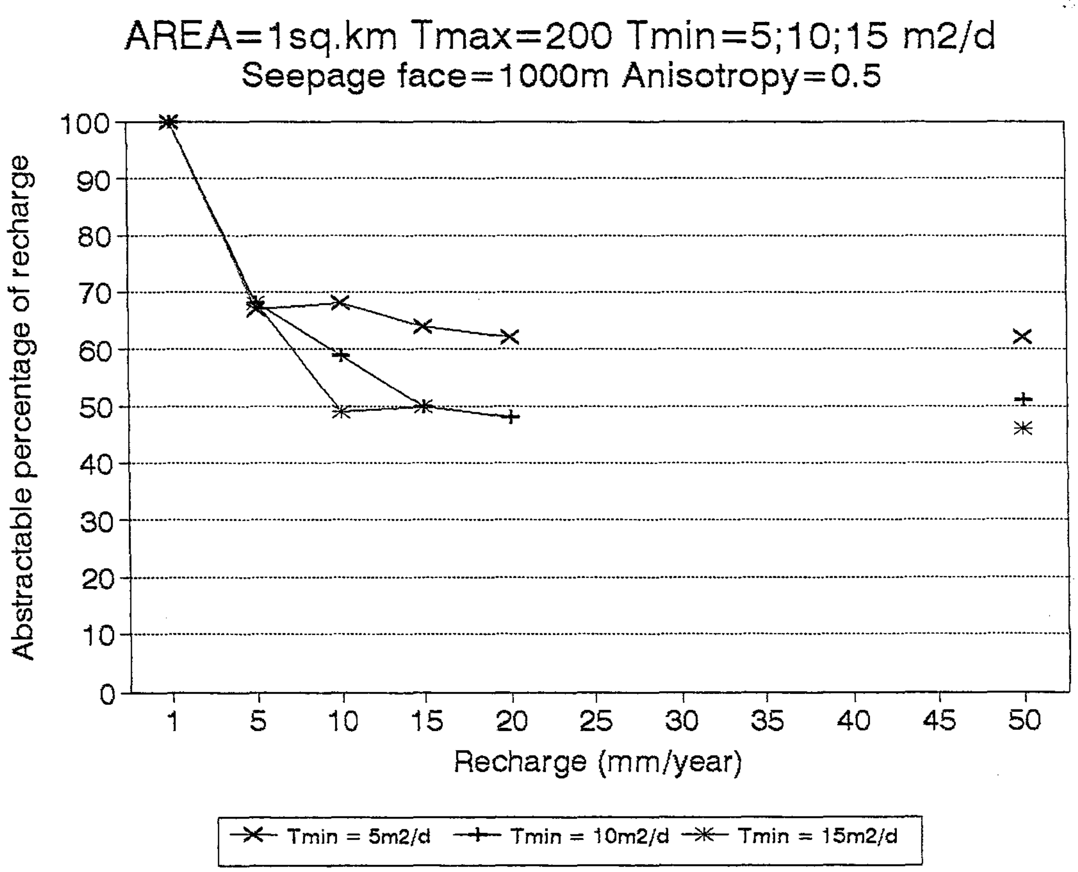
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=200 Tmin=5;10;15 m2/d
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
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5
10
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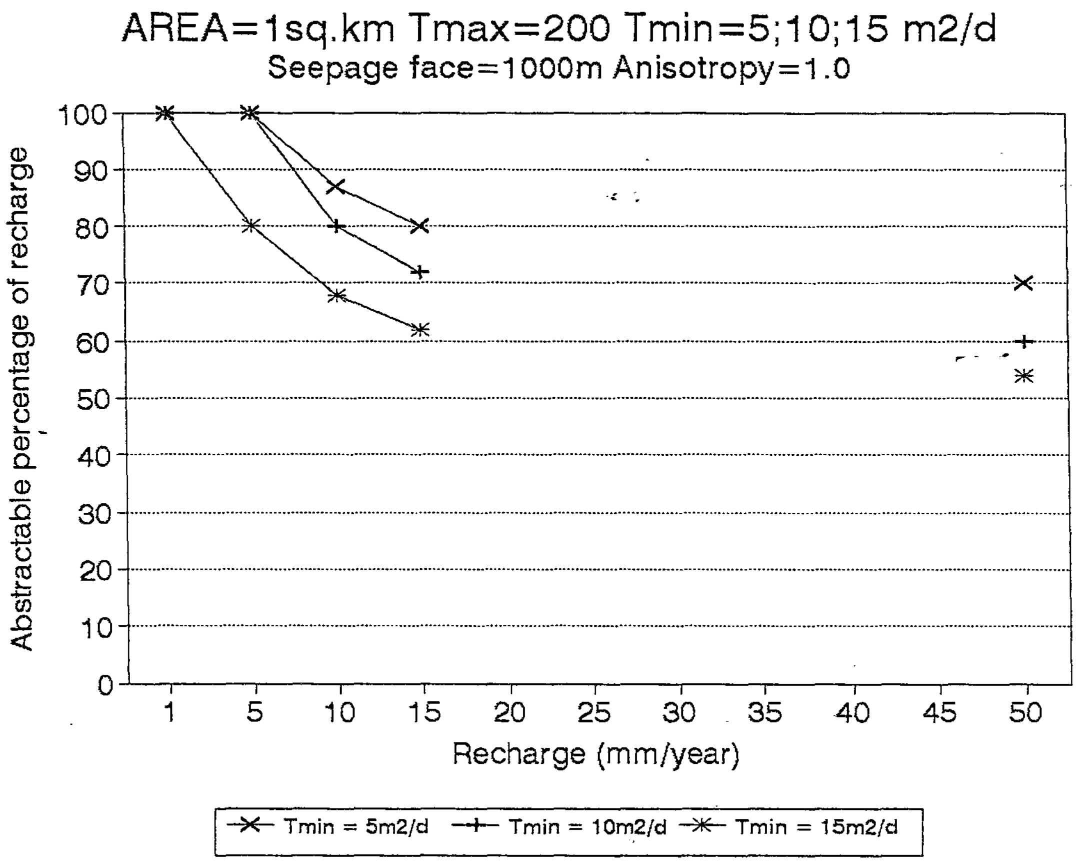
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=200 Tmin=5;10;15 m2/d
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
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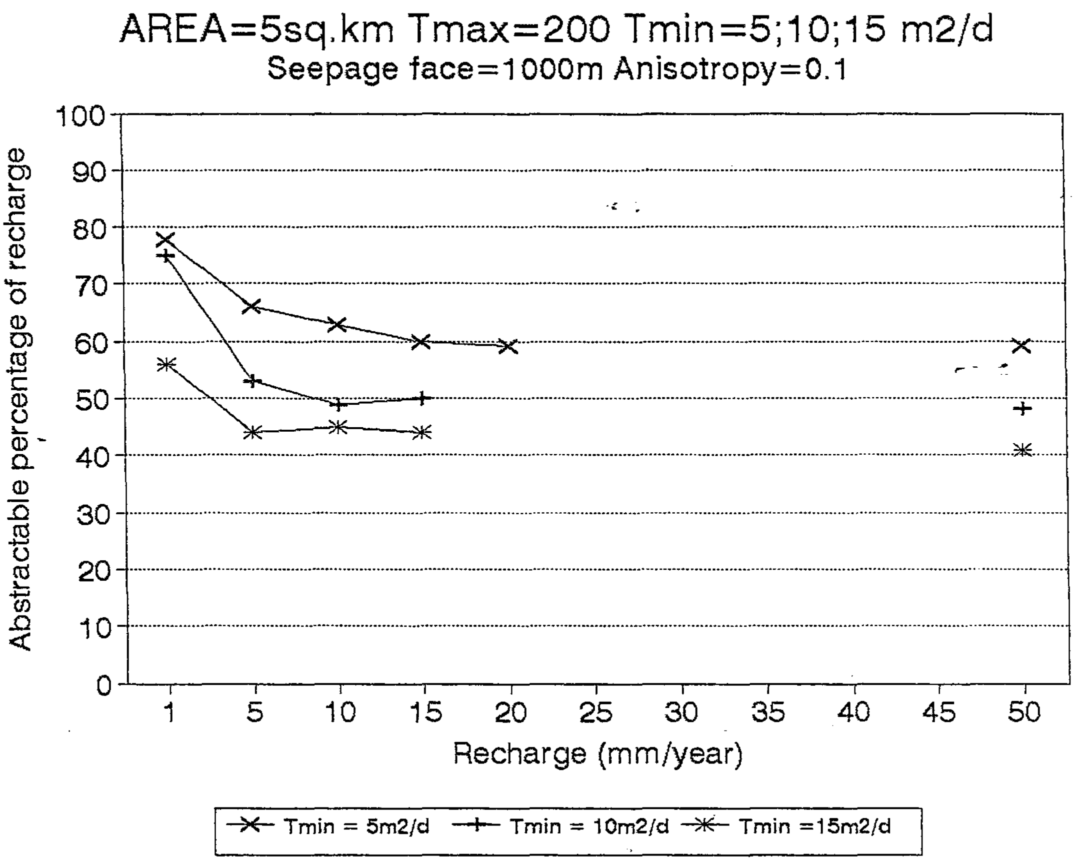
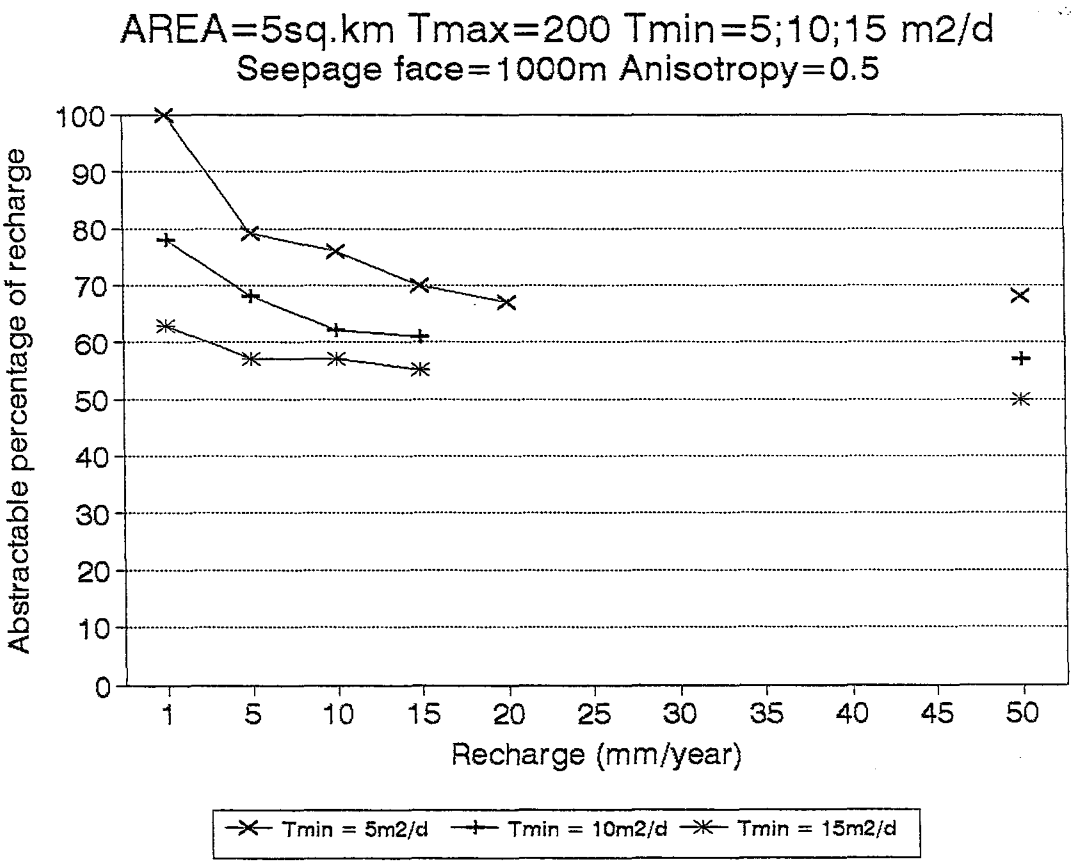
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=5sq.km Tmax=200 Tmin=5;10;15 m2/d
Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin =15m2/d


AREA=5sq.km Tmax=200 Tmin=5;10;15 m2/d
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
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25
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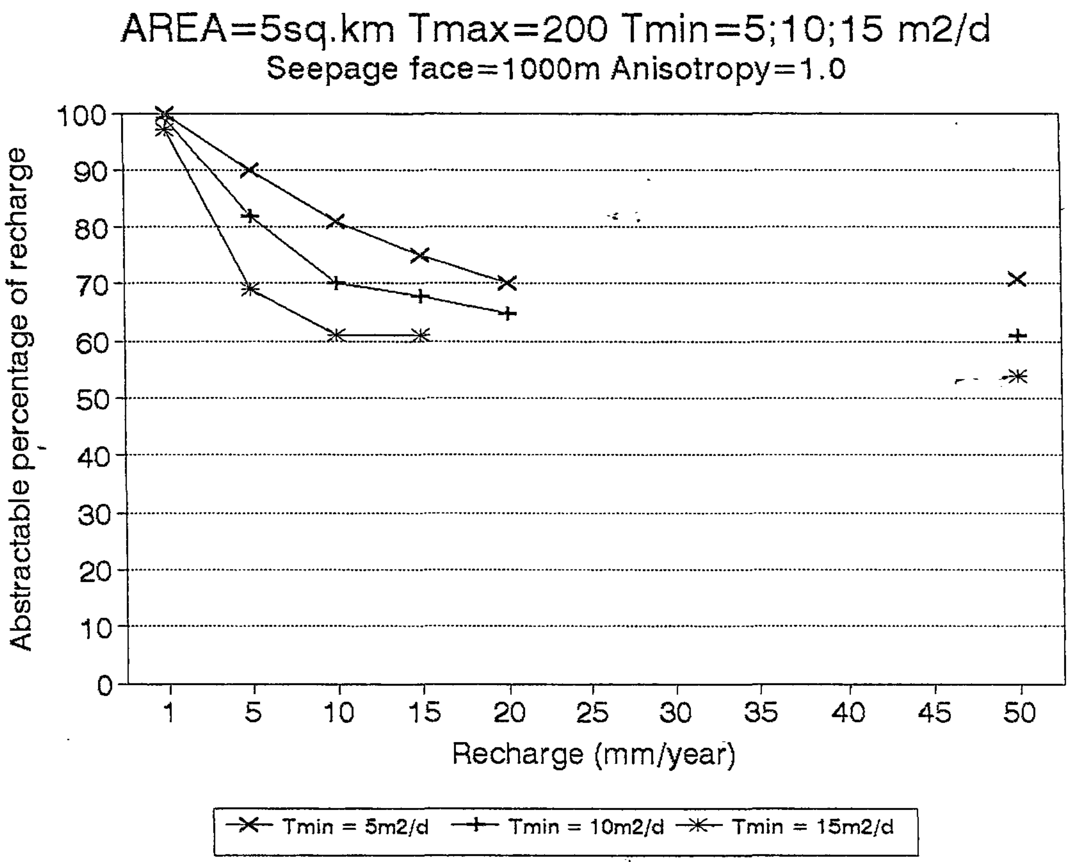
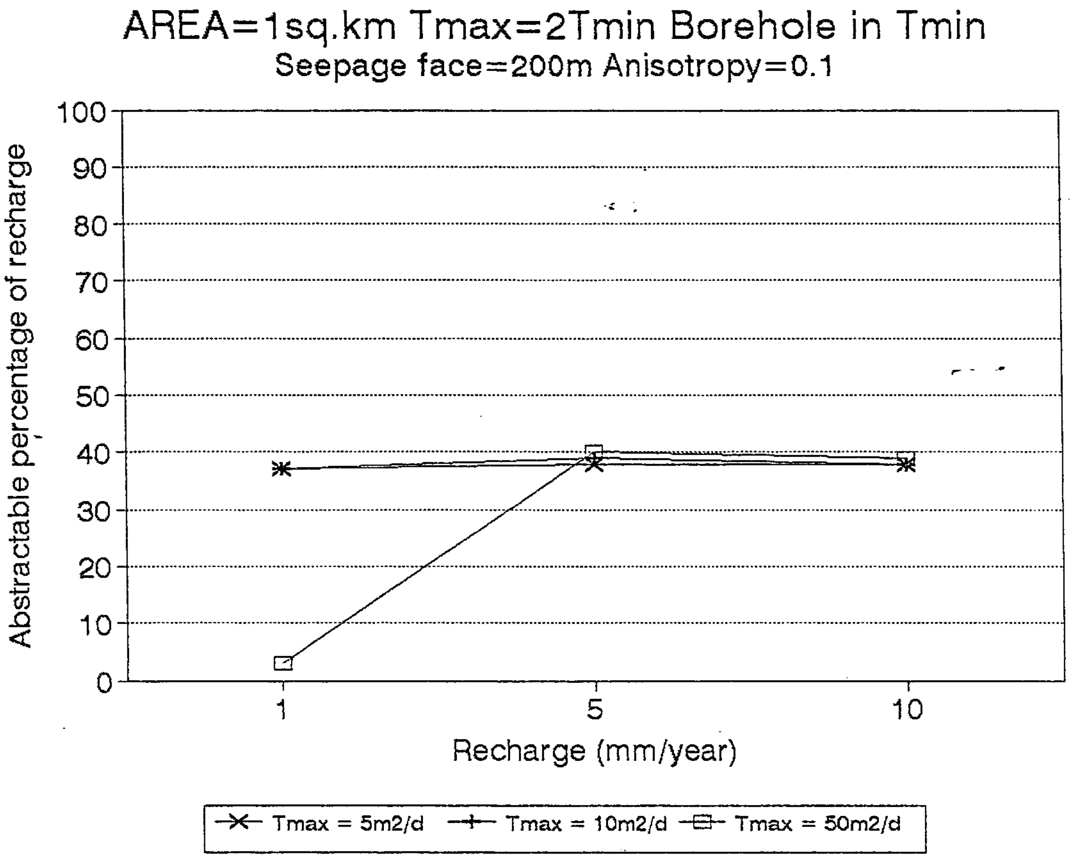
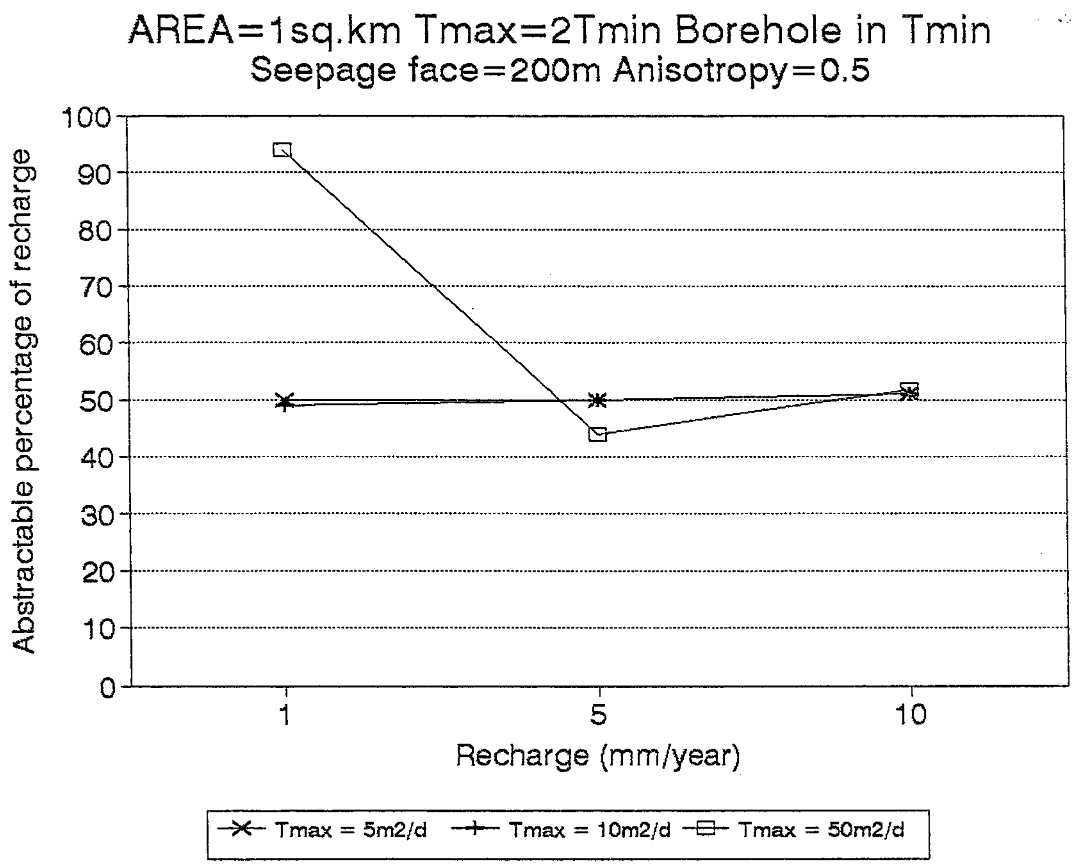
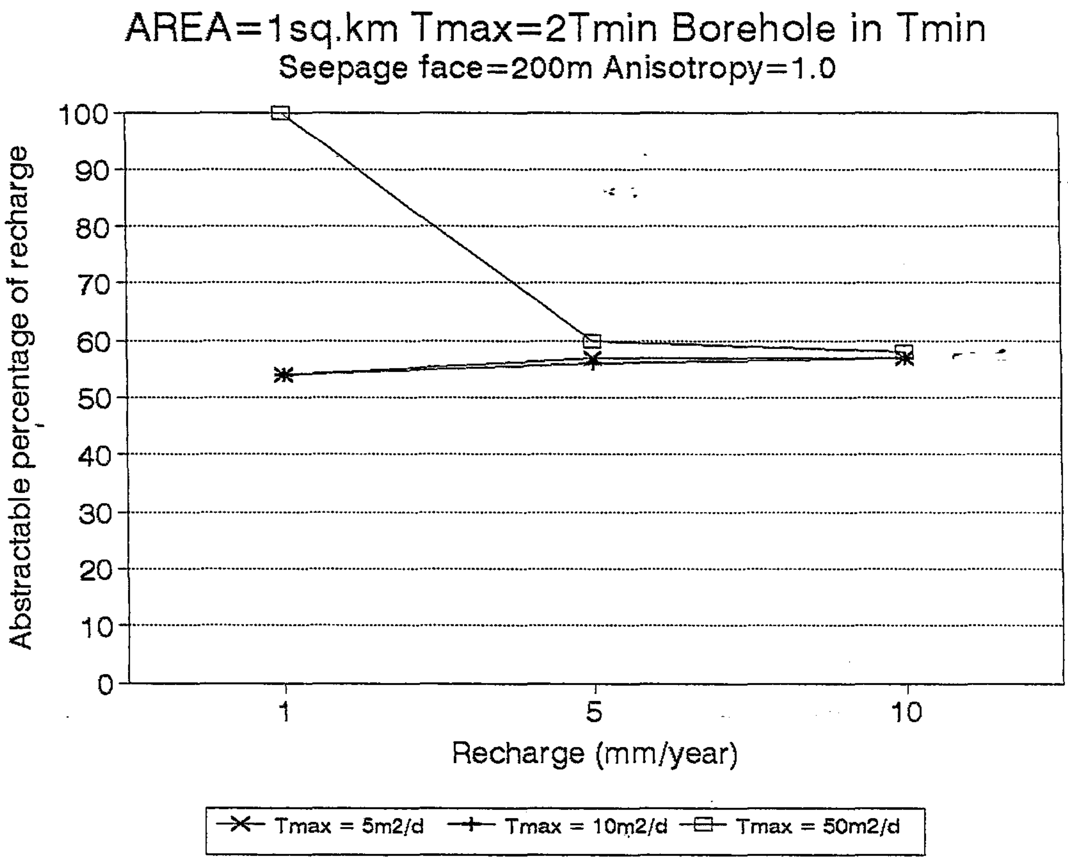
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d

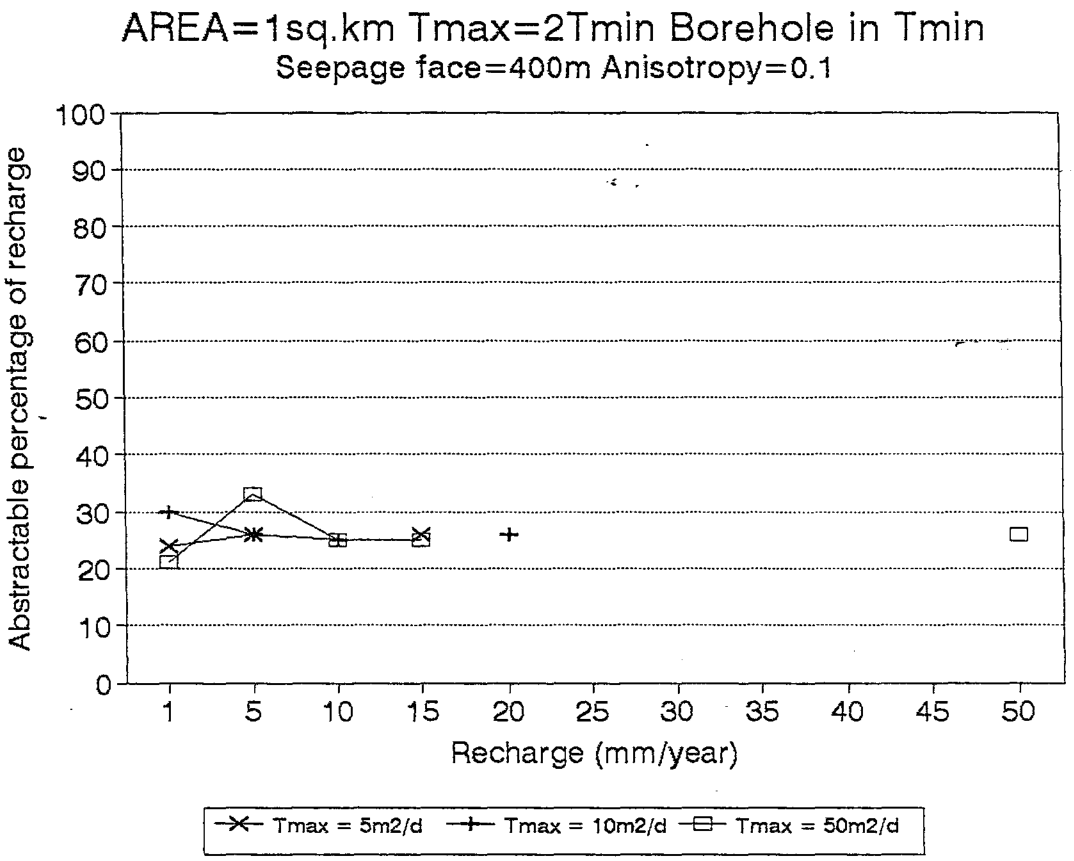

AREA=5sq.km Tmax=200 Tmin=5;10;15 m2/d
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmin = 5m2/d
Tmin = 10m2/d
Tmin = 15m2/d


AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=200m Anisotropy=0.1
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d

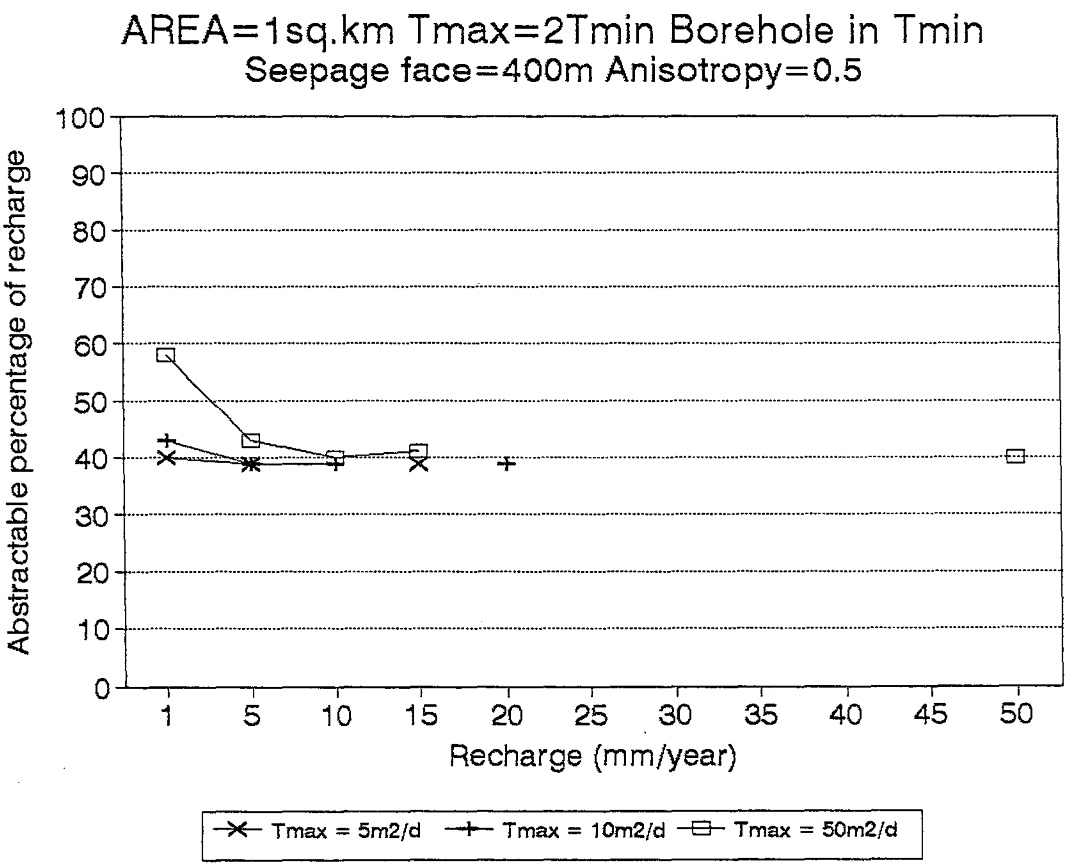

AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=200m Anisotropy=0.5
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d



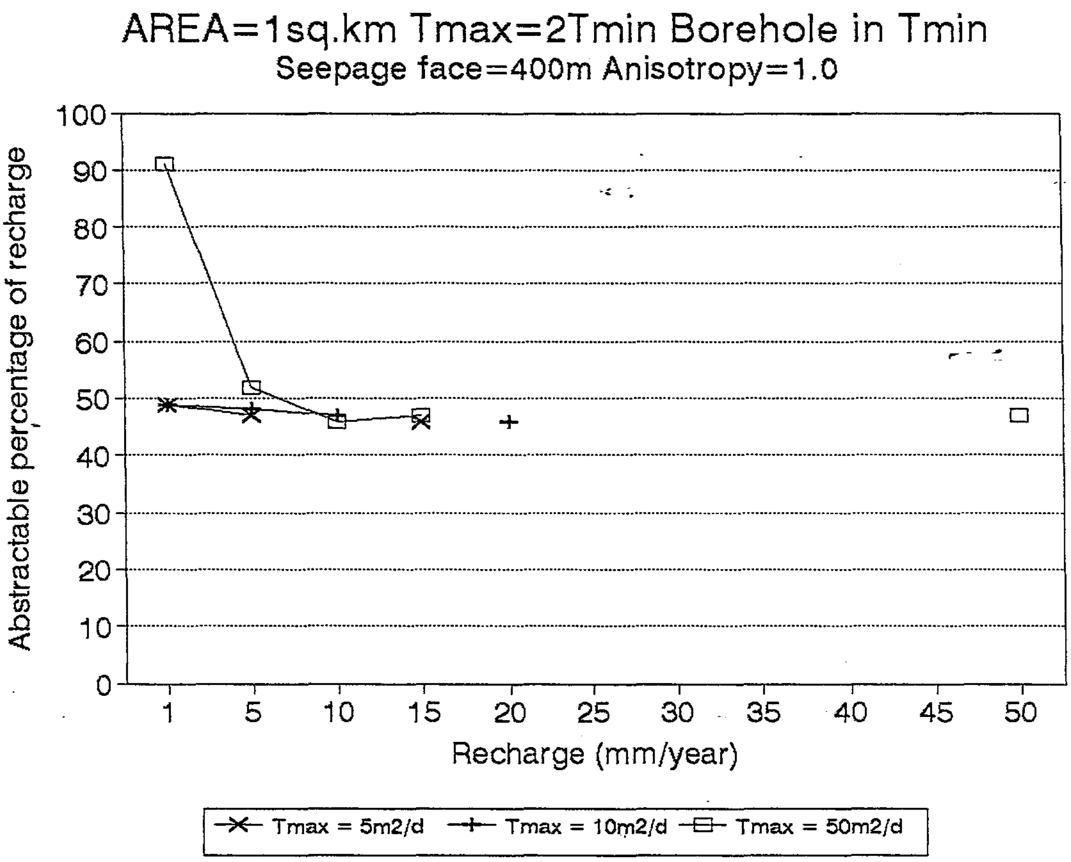
AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=200m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d



AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=400m Anisotropy=0.1
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d



AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=400m Anisotropy=0.5
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d



AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=400m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
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0
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20
25
30
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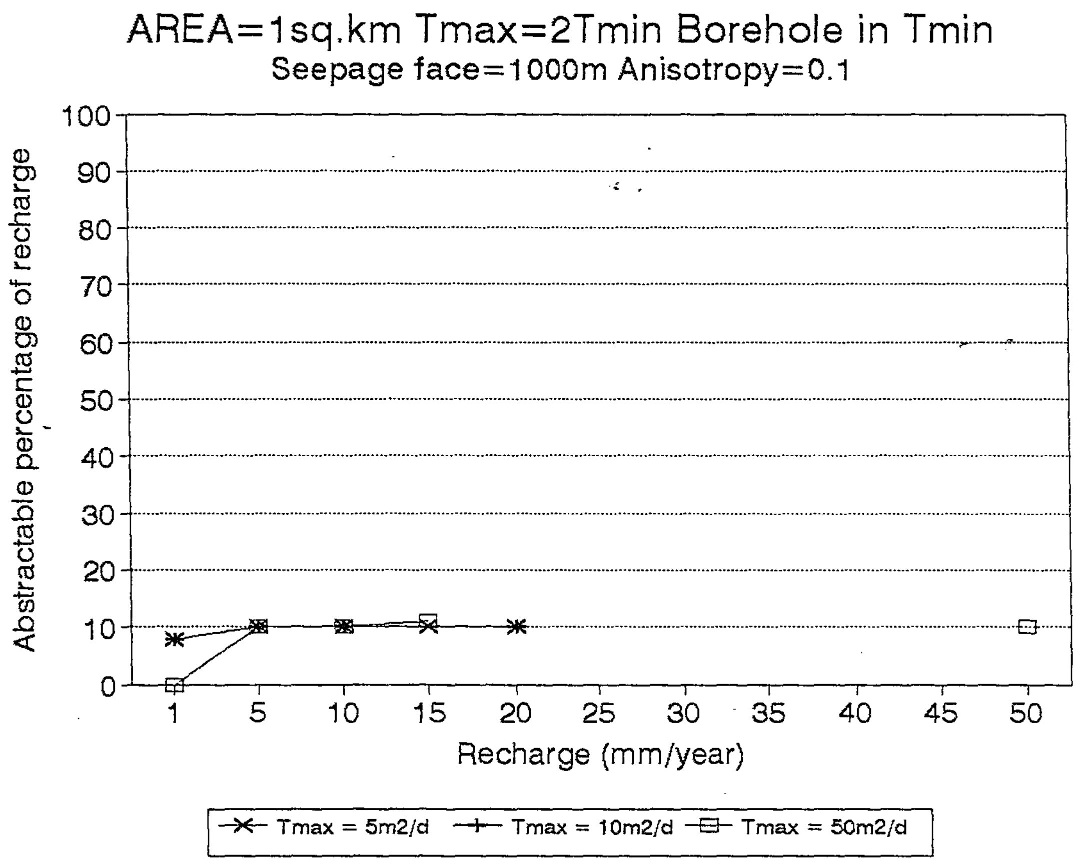
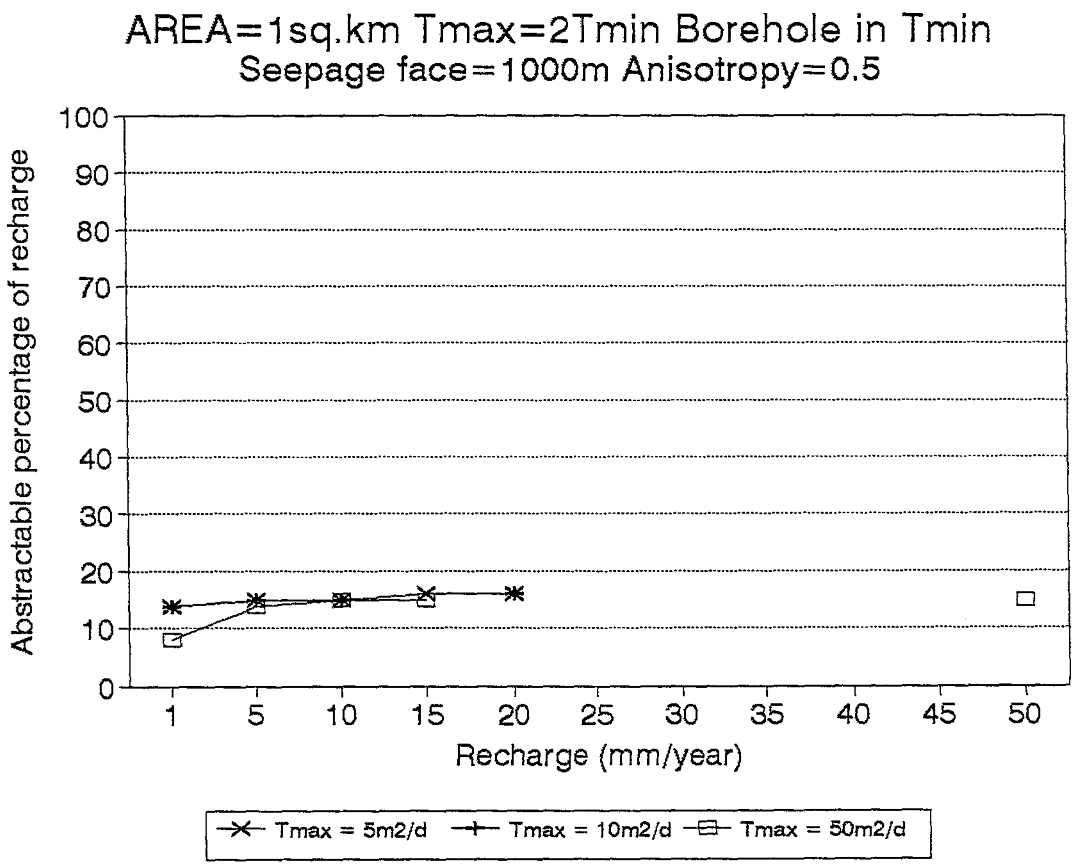
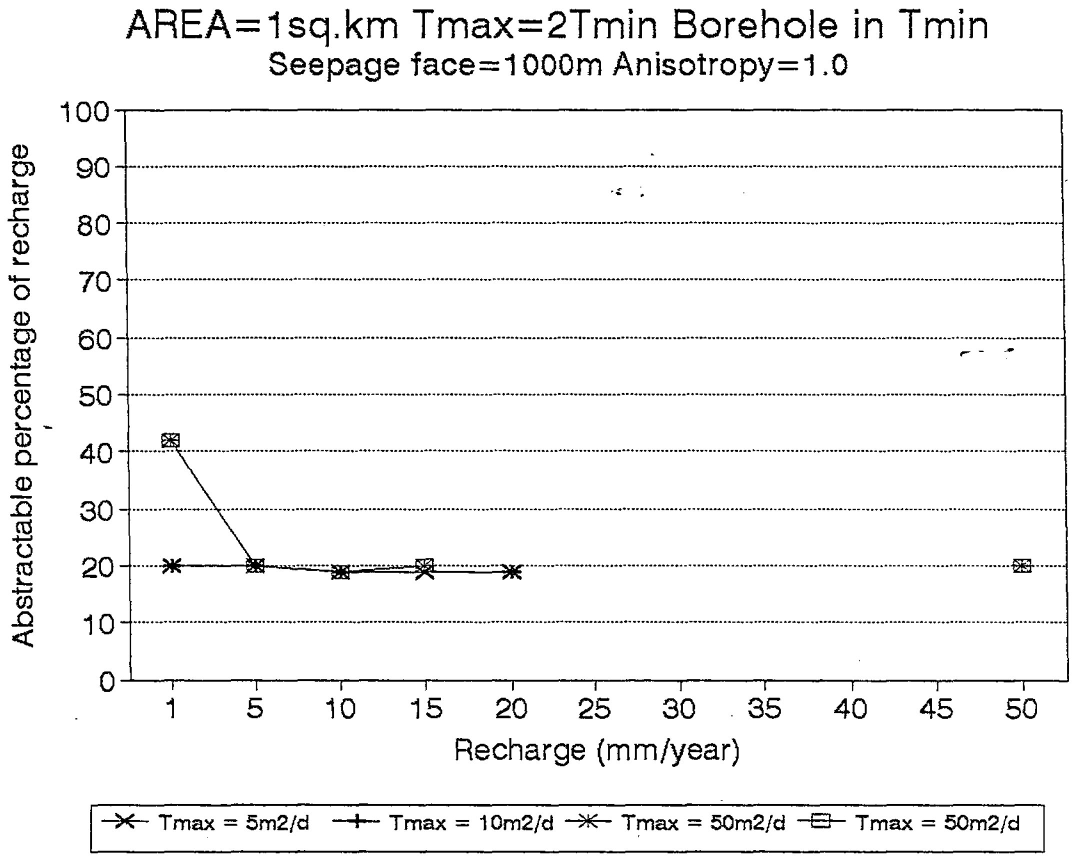
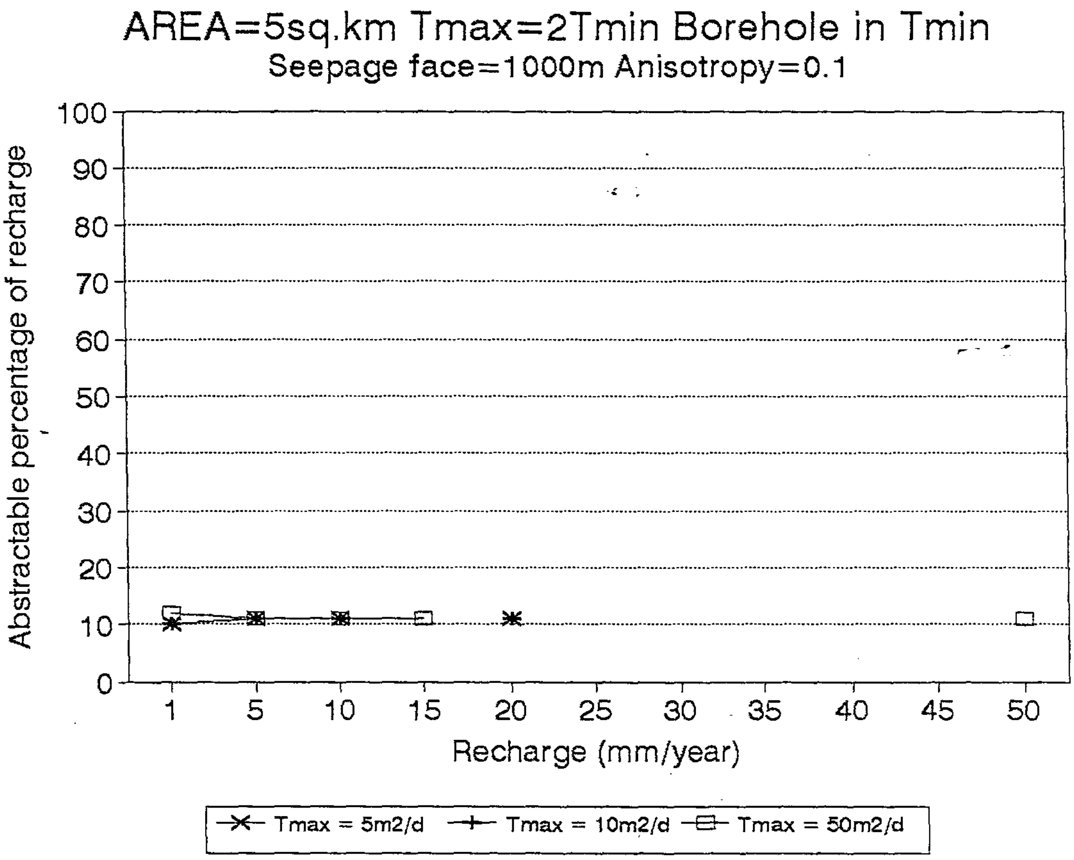
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d


AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d


AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d


AREA=1sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d
Tmax = 50m2/d


AREA=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=0.1
Abstractable percentage of recharge
0
10
20
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40
50
60
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80
90
100
1
5
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15
20
25
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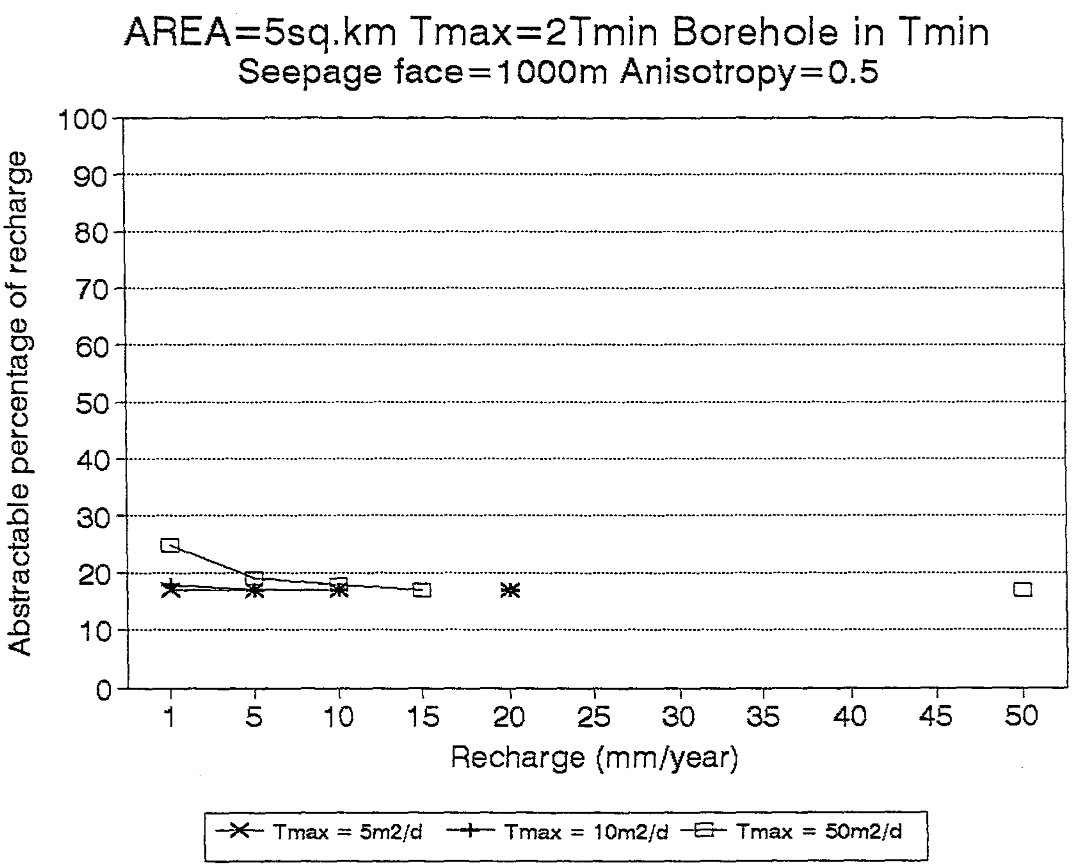
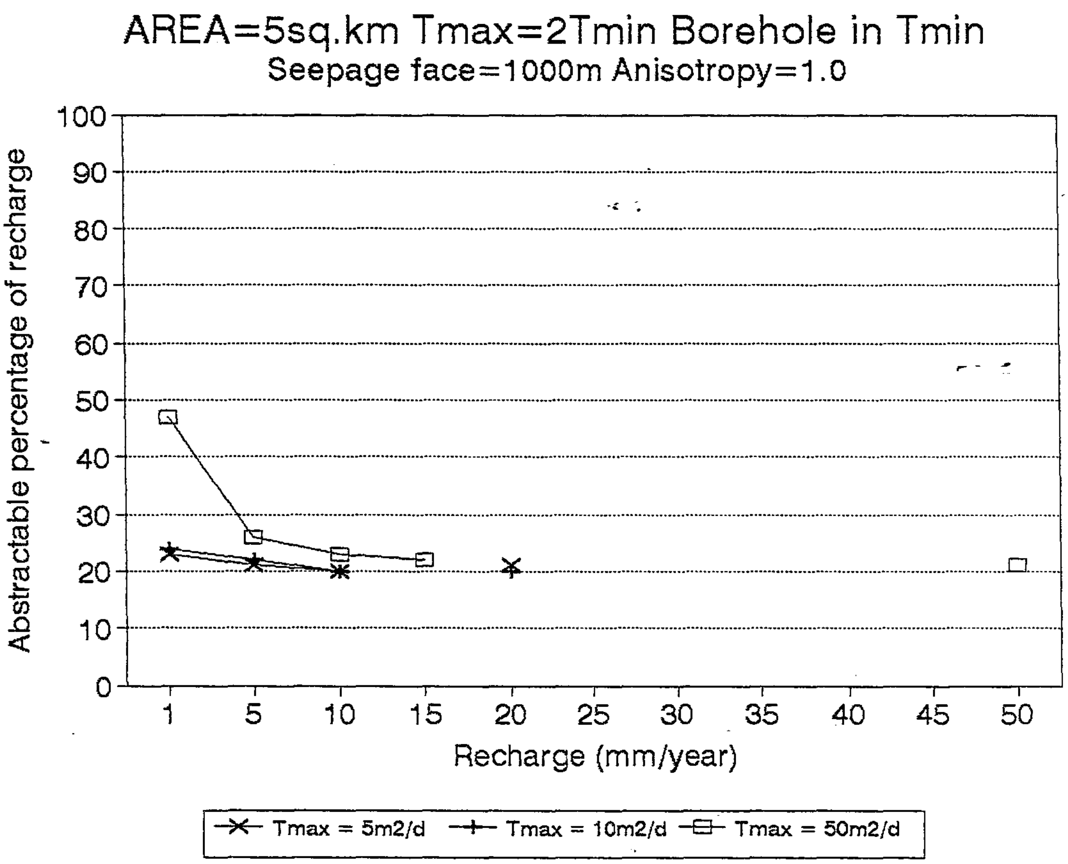
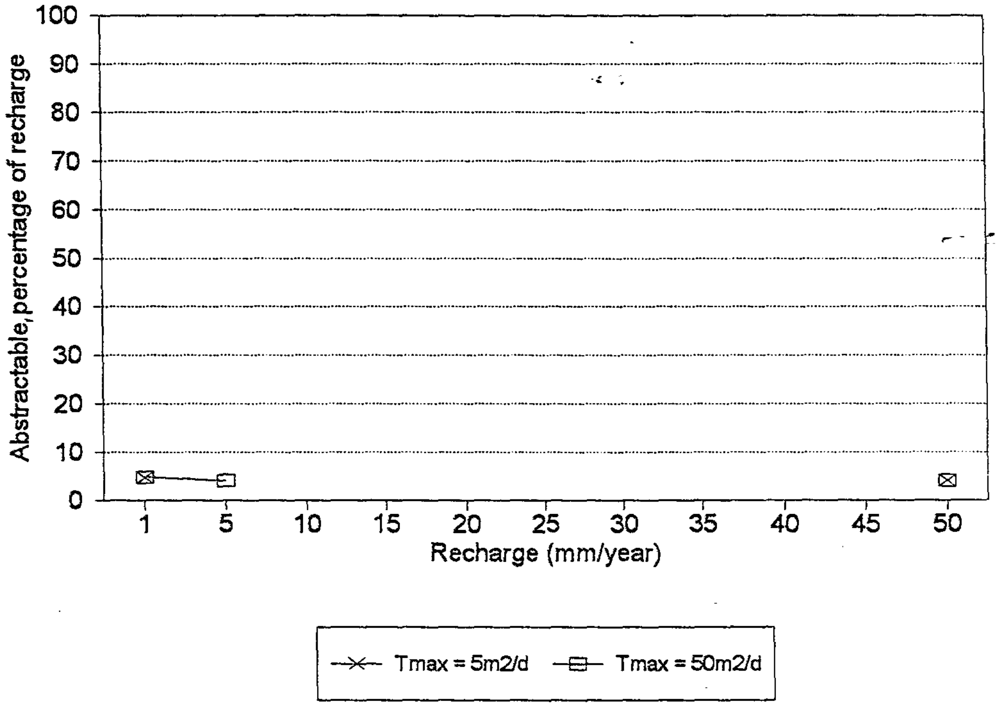
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d

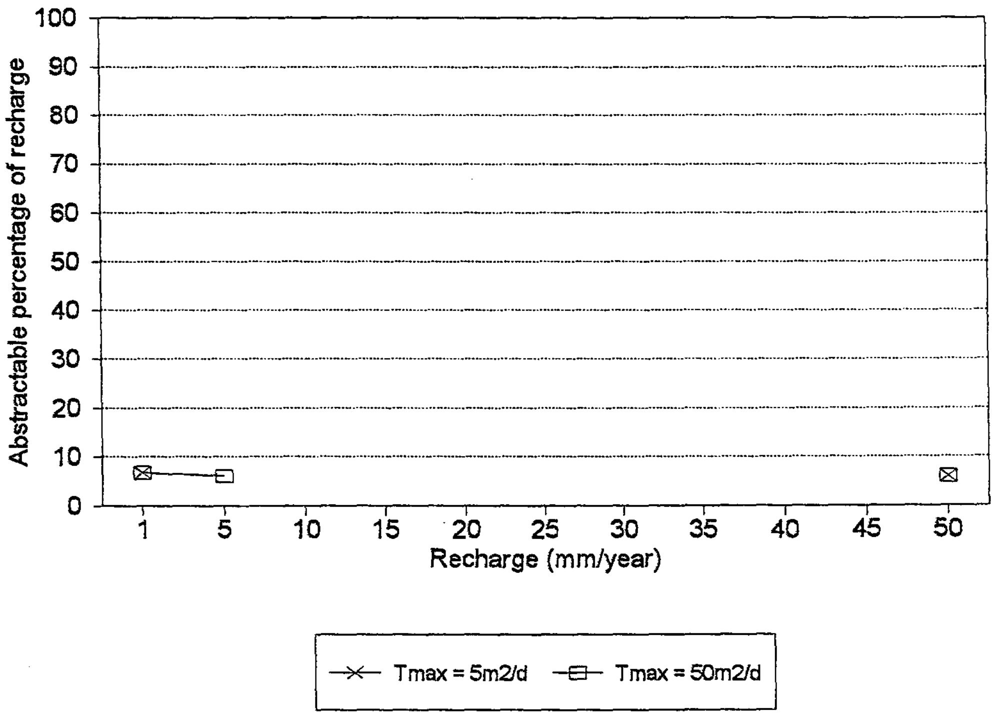

AREA=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=0.5
Abstractable percentage of recharge
0
10
20
30
40
50
60
70
80
90
100
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d

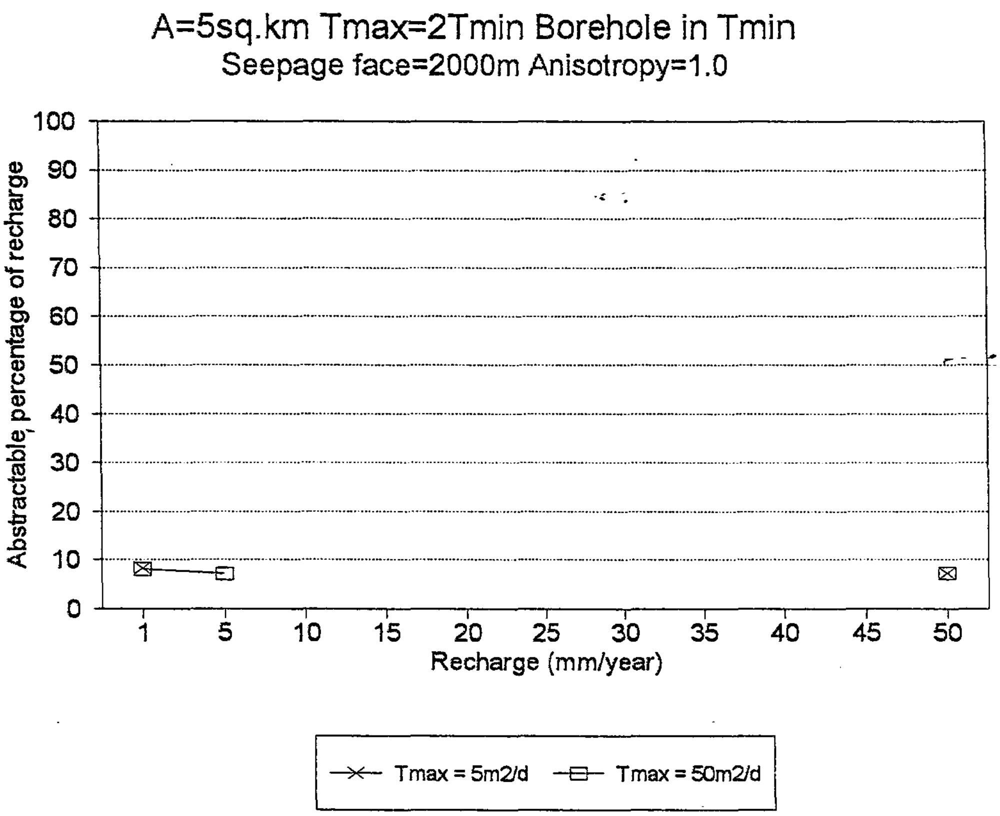

AREA=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=1000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 10m2/d
Tmax = 50m2/d

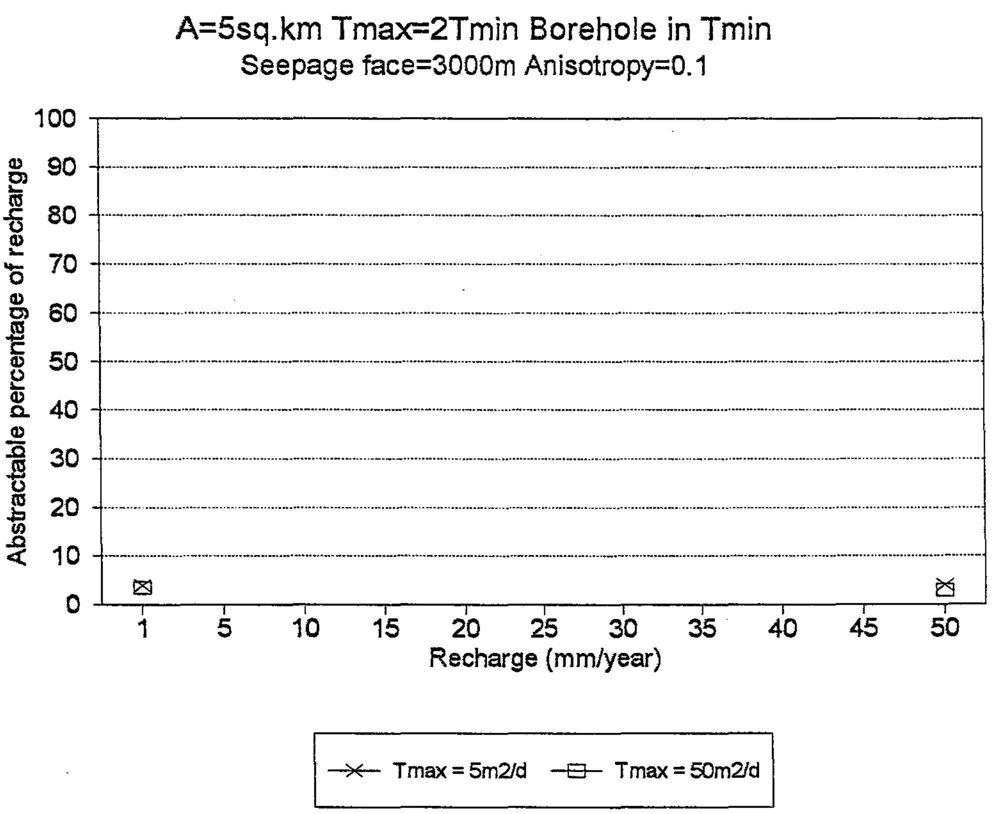
A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=2000m Anisotropy=0.1

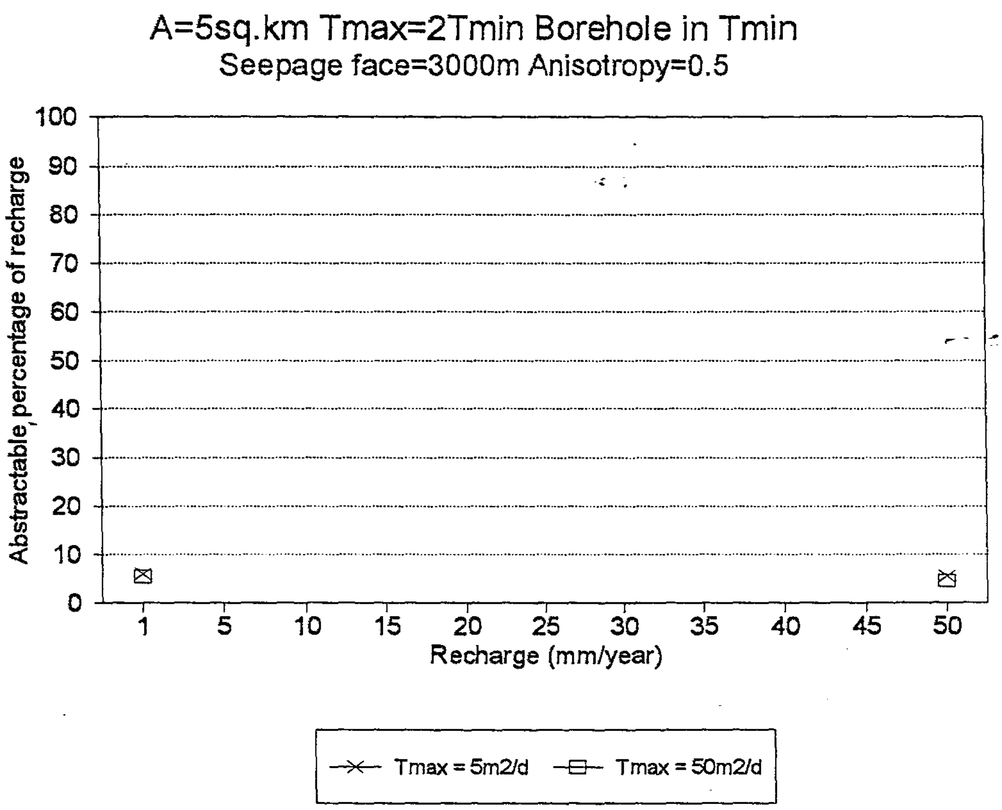


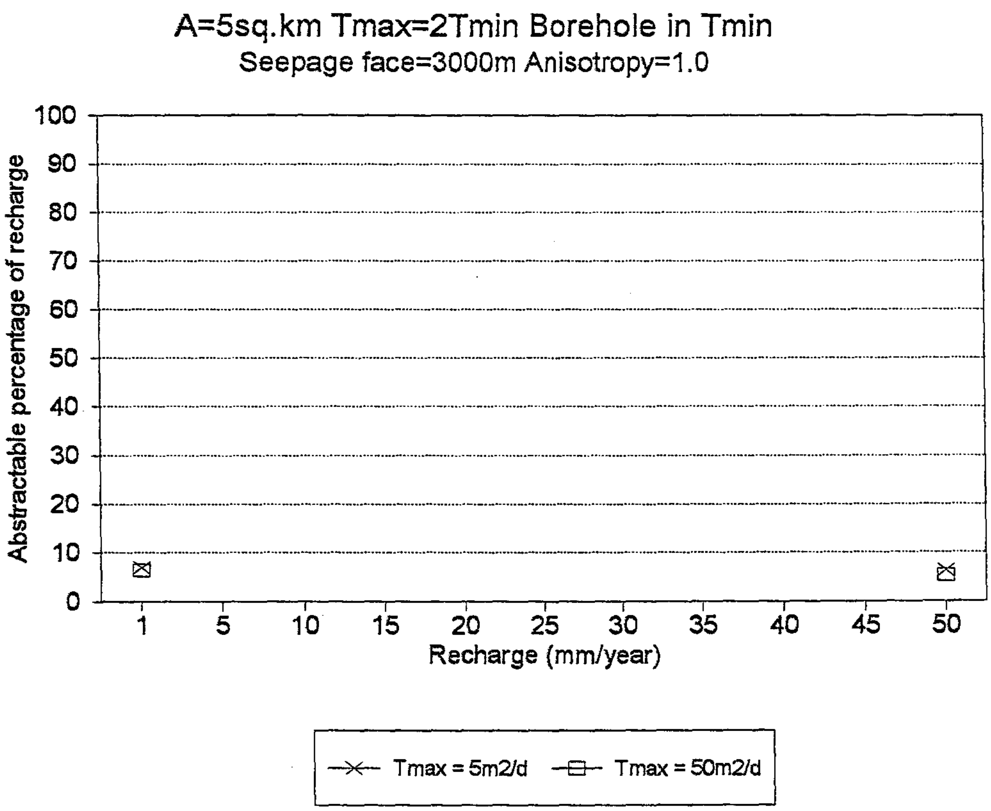
A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=2000m Anisotropy=0.5




A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=2000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d


A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=3000m Anisotropy=0.1
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d


A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=3000m Anisotropy=0.5
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d


A=5sq.km Tmax=2Tmin Borehole in Tmin
Seepage face=3000m Anisotropy=1.0
Abstractable percentage of recharge
100
90
80
70
60
50
40
30
20
10
0
1
5
10
15
20
25
30
35
40
45
50
Recharge (mm/year)
Tmax = 5m2/d
Tmax = 50m2/d

APPENDIX 2

THE 'a' AND 'c' VALUES OBTAINED USING 0.7 AS THE 'b' VALUE IN EQUATION 3.1

Tmax/Tmin = 2

Seepage face (m)		Tmax = 5m^2/day			Tmax = 10m^2/day			Tmax = 20m^2/day			Tmax = 50m^2/day		
		anisotropy			anisotropy			anisotropy			anisotropy		
-		0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0
Bh* in Tmax													
1000	a	0	0	0	0	0	0	0	0	0	0	0	0
	c	16	21	25	16	21	25	16	21	25	16	21	25
400	a	4	24	34	6	38	50	9	56	85	14	118	175
	c	39	54	60	39	54	60	39	54	60	39	54	60
200	a	8	15	15	17	22	22	35	40	40	58	70	95
	c	65	75	80	65	75	80	65	75	80	65	75	80
Bh in Tmin													
1000	a	0	0	0	0	0	0	-	-	-	0	0	0
	c	10	15	20	10	15	20				10	15	20
400	a	0	1	3	0	3	4	-	-	-	0	18	35
	c	25	39	46	25	39	46				25	39	46
200	a	0	0	0	0	0	0	-	-	-	0	30	35
	c	38	50	57	38	50	57				38	50	57

* borehole

Tmax/Tmin = 3.3; 5; 10

Borehole in Tmax

Seepage face (m)		Tmax = 50m^2/day Tmax/Tmin = 3.3			Tmax =50m^2/day Tmax/Tmin = 5			Tmax = 50m^2/day Tmax/Tmin = 10		
		anisotropy			anisotropy			anisotropy		
		0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0
1000	a	0	0	0	0	5	20	0	5	15
	c	19	27	30	24	31	36	29	41	47
400	a	10	155	95	14	70	140	21	98	200
	c	48	58	69	55	70	69	65	73	69
200	a	75	33	0	85	45	0	90	50	0
	c	70	90	100	70	90	100	70	90	100

Tmax/Tmin = 13.3; 20; 40

Borehole in Tmax

Seepage face (m)		Tmax = 50m²/day Tmax/Tmin = 3.3			Tmax =50m²/day Tmax/Tmin = 5			Tmax = 50m²/day Tmax/Tmin = 10		
		anisotropy			anisotropy			anisotropy		
		0.1	0.5	1.0	0.1	0.5	1.0	0.1	0.5	1.0
1000	a	11	57	100	10	53	150	17	40	120
	c	32	43	47	35	47	50	38	59	62

APPENDIX 3

A GUIDELINE ON STORATIVITY VALUES WHICH COULD BE USED IN THE COOPER-JACOB EQUATION

In the analysis of pump test data which is discussed in Chapter 6, an S-value is required in order to apply the Cooper-Jacob equation (eq6.10). Below are some regional S-values, and references to S-values which could be used when applying the Cooper-Jacob equation if no local value can be obtained. These values should not be used in the assessment of groundwater storage as they may differ by an order of magnitude or more from the true S-value. They can however be used in the Cooper-Jacob equation because S is logged and therefore the result obtained is not very sensitive to this value.

Regional S-value categories can be obtained from Groundwater Resources of South Africa (Vegter, 1995) or from DWAF's 1 : 500 000 hydrogeological maps. Vegter (1995) notes that the storativity value for fractured rocks is at least one order of magnitude smaller than that of the porous decomposed, disintegrated rock, regardless of fracture density.

STORATIVITY VALUES

AQUIFER	S-value	METHOD	REFERENCE
KAROO FRACTURED SEDIMENTARY ROCKS			
Dewetsdorp	0.004	Water balance	Bredenkamp, et al, 1995
De Aar	0.004	Water balance	Bredenkamp, et al, 1995
Beaufort West	0.001-0.007	Pumping test	Bredenkamp, et al, 1995
Oviston	0.0014-0.0049	-	Geological Society S.A.
Kestrell	0.000011-0.00047	-	Geological Society S.A.
Queenstown	0.000033-0.0048	Pumping test	Vandoolhaege, 1980
BASALT			
Springbok Flats	0.003-0.03	Tracers	Bredenkamp, et al, 1995
Dorps-Mogolo	0.1	Water balance	Bredenkamp, et al, 1995
LAVA (Ventersdorp)			
Sannieshof	0.01-0.02	-	Geological Society S.A.
Gemsbokpan	0.023-0.045	-	Geological Society S.A.

GRANITE			
Coetzersdam	0.00097-0.039	Various*	Bredenkamp, et al, 1995
Bulpan	0.033	-	Geological Society S.A.
Pietersburg	0.00056-0.0008	-	Geological Society S.A.
SEDIMENTARY HARD ROCK AQUIFERS			
Rietondale	0.01	Water balance	Bredenkamp, et al, 1995
PRIMARY AQUIFERS			
St. Lucia	0.3-0.4	Cl⁻ profile	Bredenkamp, et al, 1995
Atlantis	0.17	Bore cores	Bredenkamp, et al, 1995
DOLOMITE			
Zuurbekom	0.01-0.045	Various	Bredenkamp, et al, 1995
Kuruman	0.0014-0.0044	Various	Bredenkamp, et al, 1995
Zebediela	0.0027-0.0044	Various	Bredenkamp, et al, 1995
Grootfontein	0.023	Hydrograph	Bredenkamp, et al, 1995
Wondergat	0.019	Hydrograph	Bredenkamp, et al, 1995
Western Areas	0.01-0.045	Various	Bredenkamp, et al, 1995
Pering	0.001-0.0037	Various	Bredenkamp, et al, 1995
Potgietersrus	0.001-0.0037	Various	Bredenkamp, et al, 1995
Rietpoort	0.026-0.046	Various	Bredenkamp, et al, 1995

* Various: More than one of the following methods: Water balance (saturated volume fluctuation), hydrograph, pumping test, cumulative rainfall departure method (CRD), direct parameter estimation method (DPE).

References:

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J. and Van Rensburg, H.J. 1995.
Manual on quantitative estimation of groundwater recharge and aquifer storativity. Water Research Commission Report No. 353. Pretoria, South Africa.

Geological Society of South Africa.
An Introduction to Ground Water. Groundwater Division, Geological Society of South Africa.

Vandoolhaeghe, M.A.C. 1985.
The development of an assured water supply for the municipality of Beaufort West. Technical Report Gh 3299, Directorate of Geohydrology, Department of Water Affairs and Forestry, South Africa.