A SPATIAL DECISION SUPPORT SYSTEM FOR GROUNDWATER ABSTRACTION IMPACT ASSESSMENT AND LICENSING
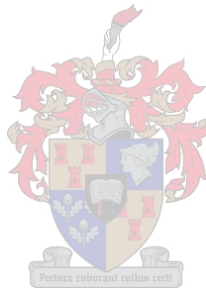
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Thesis presented in partial fulfilment of the requirements for the degree of Master of Natural Sciences at the University of Stellenbosch.

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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

ABSTRACT

Water resources in South Africa are limited and groundwater plays an important role in supporting basic human needs, sustaining ecosystems and enabling industrial and agricultural development. Sound management practices are necessary to ensure sustainable development of water resources. All groundwater usage must be licensed in compliance with the National Water Act of 1998. A Spatial Decision Support System (SDSS) can be used to assist in the groundwater usage licensing process of the Department of Water Affairs and Forestry (DWAF).

The main aim of this study was to develop a SDSS, named Groundwater Abstraction & Licence Evaluation Tool (GALET), that could assist in the process of allocating water use licences and determining the local impact of abstraction, based on existing theory and data. The development was done within ArcView 3.2 using the scripting language Avenue. The Sandveld, an arid stretch of land along the west coast of South Africa that is heavily impacted by groundwater abstraction, was the chosen study area. The data collected for this study included existing borehole, recharge, rainfall and geological information.

GALET proved to be capable of calculating essential information needed to evaluate groundwater abstraction, which included drawdown in the water table, zone of influence and the possible effects on features such as rivers and wetlands. Targeted potential users regarded GALET as a useful tool in the process of licensing and groundwater abstraction impact assessment and plans are under way to implement GALET or a derivative thereof at the DWAF regional offices.

OPSOMMING

Waterhulpbronne in Suid-Afrika is beperk en grondwater speel 'n belangrike rol in die ondersteuning van basiese menslike behoeftes, volhouding van ekosisteme asook industriële en landbou-ontwikkeling. Betroubare bestuurspraktyke is noodsaaklik om die volhoubare ontwikkeling van waterhulpbronne te verseker. Alle grondwatergebruik moet volgens die Nasionale Waterwet van 1998 gelisensieer word. 'n Ruimtelike Besluitnemings Ondersteuning Stelsel (RBOS) kan as 'n hulpmiddel gebruik word in die lisensiëringsproses van die Departement van Waterwese en Bosbou.

Die hoofdoel van hierdie studie was om 'n RBOS, genoem Groundwater Abstraction & Licence Evaluation Tool (GALET), te ontwikkel wat as hulpmiddel gebruik kan word in die allokeringsproses van watergebruiklisensies en die bepaling van die impak van grondwateronttrekking op die omgewing, gebaseer op bestaande teorie en data. Die ontwikkeling is in ArcView 3.2 met die programmeringstaal Avenue gedoen. Die Sandveld, 'n ariede streek aan die weskus van Suid-Afrika wat onderhewig is aan grootskaalse grondwateronttrekking, is gekies as die studie area. Die data wat vir hierdie studie ingesamel is sluit bestaande boorgat, grondwateraanvulling, reënval en geologiese inligting in.

GALET was in staat om belangrike inligting aangaande die evaluering van grondwateronttrekking te bereken, o.a. die daling van die grondwatervlak, die impaksone en die moontlike effekte op landvorms soos riviere en vleilande. Die teikengroep potensiële gebruikers het GALET as 'n nuttige hulpmiddel in die proses van lisensiëring en grondwateronttrekking impakbepaling beskou en planne is onderweg om dit of 'n aangepaste program by die streekskantore van die Departement van Waterwese en Bosbou te implementeer.

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CONTENTS

TABLES

FIGURES

ABBREVIATIONS

CFR	-	Calculated Fixed Radius
DD	-	Decimal Degrees
DMS	-	Degrees/Minutes/Seconds
DWAF	-	Department of Water Affairs and Forestry
GALET	-	Groundwater Abstraction & Licence Evaluation Tool
GEOSS	-	Geohydrological and Spatial Solutions
GIS	-	Geographic Information System
GUI	-	Graphical User Interface
ha	-	Hectare
IWRM	-	Integrated Water Resources Management
km	-	kilometre
km^2	-	square kilometres
L/s	-	litres per second
m	-	metre
m/d	-	metre per day
m^2/d	-	square metre per day
m^3	-	cubic metre
m^3/a	-	cubic metre per annum
m^3/d	-	cubic metre per day
m^3/ha/a	-	cubic metre per hectare per annum
mbgl	-	metres below ground level
mm	-	millimetre
mm/a	-	millimetre per annum
NGA	-	National Groundwater Archive
NGDB	-	National Groundwater Database
NWA	-	National Water Act
REGIS	-	Regional Geohydrological Information System
S	-	Storativity
SAGIS	-	Santa Ana Geographic Information System
SQL	-	Standard Query Language
SDSS	-	Spatial Decision Support System
T	-	Transmissivity
WARMS	-	Water Application and Registration Management System
WMS	-	Water Management System
WGS84	-	World Geodetic System, 1984
ZOC	-	Zone of Contribution
ZOI	-	Zone of Influence

CHAPTER 1: INTRODUCTION

1.1 IMPORTANCE OF GROUNDWATER RESOURCES

In many parts of the world, groundwater plays a vital role in water supply for environmental, economic and domestic purposes (Sililo 2000). Despite the importance of groundwater resources, their sustainability is threatened by over-abstraction and pollution. South Africa's water resources are under continuous stress because of increasing agricultural, industrial and domestic use (South African Department of Foreign Affairs, 2001). In addition, South Africa is subject to extreme climatic conditions, such as recurring droughts, which may last for several years (Scott, Fairbanks & Le Maitre 1998). Therefore, the issue of water management is becoming increasingly complex and improved methods are essential for ensuring successful, sustainable groundwater resource management. Such improved methods include decision support tools based on geographic information and spatial data.

Two-thirds of South Africa's surface area is dependent on groundwater. Groundwater makes a relatively small contribution (13%) to the national bulk water supply, but it represents an important and strategic water resource in South Africa. Although groundwater is predominantly used for irrigation, it is also used for domestic purposes in more than 300 towns and smaller settlements.

1.2 NATIONAL WATER ACT OF 1998

The National Water Act of 1998 (NWA) is a redraft of the Water Act of 1956 (Act Nr. 54 of 1956). With the new democratic government of 1994, the water law inevitably had to be changed to supply the water needs of people who had been denied access to water for productive use in the past (Vegter 2001). The purpose of the Act is to ensure that the nation's water resources are protected, used, developed, conserved, managed and controlled in ways that support current and future needs. The NWA recognises "...the need for the integrated management of all aspects of water resources and, where appropriate, the delegation of management functions to a regional or catchment level so as to enable everyone to participate..." and that "...the ultimate aim of water resources management is to achieve the sustainable use of water for the benefit of all users..." (South Africa 1998, p.2). Thus, according to the Constitution of South Africa, it is every person's right to have access to clean water resources (South African Department of Foreign Affairs 2001).

With the introduction of the new National Water Act of 1998, attitudes towards the management and protection of water resources had to be changed drastically. Not only does the NWA recognise the goals of protection and conservation, but it also reflects the reality of the impacts associated with water use. Integrated water resource management (IWRM) provides a framework that is intended to safeguard water resource quality against unsustainable practices. IWRM makes use of a system of source controls and resource protection measures. Source-directed measures include a range of regulatory controls aimed at the sources of impacts on water resources, such as limitations on abstractions.

Water use is allocated according to a resource class, which can include the use of certain water resources for disposal of waste discharges. Water resources classified as sensitive or environmentally important may be strictly controlled, with water use allocations limited to minimise harmful impacts. Measurements for water usage must be set to ensure that boreholes are located optimally while minimising localised impacts of pumping on sensitive aquatic ecosystems (Wright & Xu 2000).

1.3 GROUNDWATER DEVELOPMENT

According to Vegter (2001), groundwater usage and borehole drillings have increased considerably over the past fifty years. It is estimated that 2000 boreholes were drilled in 1910, while approximately 12500 and 56000 boreholes were drilled in 1955 and 1985 respectively. This represents growth rates of 3.8% between 1910 and 1955 and 5% from 1955 to 1985. Based on these growth rates, it is estimated that between 94000 and 110 000 boreholes were drilled in 1999. Assuming a success rate of 50% for borehole drillings and that one-quarter of the successful boreholes drilled since 1950 are replacements for "dried-up" or collapsed holes, it is estimated that there were 56 000 and 110 000 water-yielding boreholes in existence in 1980 and 1999 respectively (Vegter 2001). The National Groundwater Database (NGDB) of August 1997 and January 2000 indicates that the total number of boreholes drilled at the time were 189 234 and 206 000 respectively (DWAF 2003). Not all of the boreholes in the NGDB were being used at the time as production boreholes – some of the older boreholes had been closed as a result of over-abstraction - but they were still listed in the NGDB.

The increase of groundwater usage, according to the data collected by Vegter (2001), can be seen in Figure 1.1. The maximum quantity of groundwater that can be abstracted without any

adverse effect in terms of a safe yield is estimated at about 5400 Mm^3/a. Even though this quantity is considerably more than the current estimated use, the abstraction rate is in excess of the recharge rate (Hazelton, Nkhuwa & Robinson 2002). This excess rate is damaging aquatic ecosystems and/or is making it impossible to satisfy the basic and developmental needs of people who are now, or who will be, relying upon water from the relevant resource.
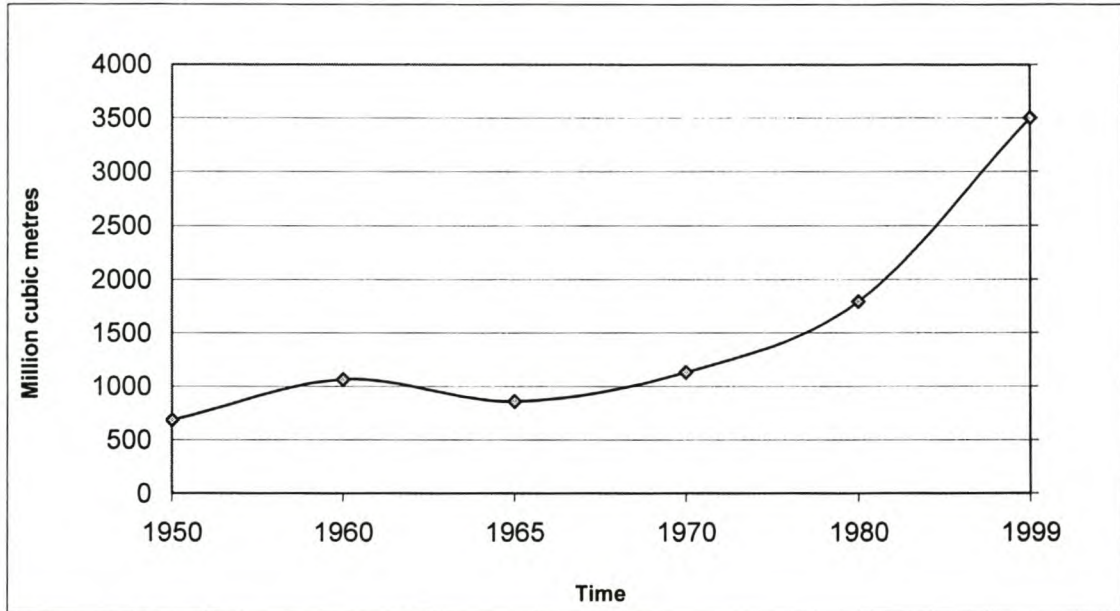
Figure 1.1: Increasing groundwater usage in South Africa over the past 50 years.

The negative ecological impacts of excessive abstraction also include (Peralta 1995):

- an increased salinity in the water and soil, especially in coastal zones;
- potential chemical groundwater contamination;
- reduced river flow due to a smaller contribution to base flow by the aquifer or an increased recharge contribution from the river to the aquifer; and
- declining water levels in wetlands.

1.4 EXISTING GROUNDWATER MANAGEMENT TOOLS

Water resource management requires the collection of a vast variety of data. There are currently only a few groundwater information systems available in South Africa that can handle the data needed for water resource management (Blecher 2000). These water related databases, e.g. NGDB, the National Groundwater Archive (NGA), Water Application and Registration Management System (WARMS) and Water Management System (WMS), mainly reside at government departments and institutions such as the Directorate: Geohydrology and are not openly available to outside users and other computer based water

related applications. The largest volume of accurate and reliable data is within private organisations, but due to the lack of common interest or unwillingness to share, most of these data are not included in extensive groundwater databases such as the NGDB.

For sustainable usage, it is necessary to monitor, allocate and license the amount of groundwater that is abstracted, once basic human needs and aquatic ecosystem requirements have been met. Boreholes and abstraction points must be managed individually for optimal usage and to prevent negative ecological impacts. A groundwater abstraction model can be used to obtain optimal usage parameters such as water level and yield for each active abstracting borehole (Bear & Verruijt 1992). To date, the processes of water allocation and borehole management have been based on the specialist experience and knowledge of DWAF personnel. To address the potential subjectivity of the groundwater allocation process, particularly in areas away from a specialist knowledge base, a well-populated GIS would be a practical supporting tool (Conrad 2003, pers com). A GIS in the form of a SDSS with modelling capabilities can serve as a tool for groundwater resource management at a spatial level (ESRI 2003; Cozad, Oldenburg & Vitt 1998).

DWAF is currently using an ArcView/Oracle application developed in the Netherlands called Regional Geohydrological Information System (REGIS). REGIS is a hydrogeological information system, in which all relevant hydrogeological and related data are stored, managed, manipulated and queried in a uniform way. REGIS can be used for the evaluation of geohydrological situations on a national and regional scale. However, REGIS is not utilised in the process of evaluating groundwater abstraction and usage requests and does not consist of modules to determine the impact of abstraction for a specified borehole under various conditions.

1.5 SPATIAL DECISION SUPPORT SYSTEMS
Although GIS are valuable tools for effective water resource management (Van Riet et al 1994) and GIS software packages such as ARC/INFO and ArcView GIS are widely used to create and maintain spatial data on water supplies, water usage, soils, groundwater, water quality and topography at national and local levels, the proper use and management of a water resource requires a certain degree of expertise. Project managers and people in decision-making positions often lack the necessary skills to use these systems and do not have instant access to GIS analysis results.

To overcome limitations, Spatial Decision Support Systems (SDSS) are emerging as valuable tools for managing natural resources such as land and water (Dutta 1998). SDSS are user-friendly tools that help analyse and manipulate GIS data (Rossouw 2000). SDSS are normally built on an existing GIS, but with an easy-to-use interface that makes use of the existing GIS capabilities. A SDSS provides the following unique advantages for managing land and water resources:

- It represents the spatial relationships of the real world in a visual and analytical form.
- It includes a comprehensive database, which is the basis for the integration of socio-economic, environmental and physical components of the real world.
- It has modelling capability, which can integrate simulation/optimisation techniques to solve complex natural resources management problems.

Therefore, if implemented correctly, a SDSS can be a means of making the process of groundwater management easier for the relevant authorities.

1.6 RESEARCH PROCESS AND METHODOLOGY

This study aims to develop a SDSS, called GALET (Groundwater Abstraction & Licence Evaluation Tool), that will assist in the process of allocating water use licences and determining the local impact of abstraction, based on existing theory and data. The development will be done within ArcView 3.2 using the scripting language Avenue.

The goals of the research are:

1. Data collection and evaluation: determine data requirements, obtain and evaluate data.
2. Prototyping: construct a preliminary application system for analysis on test data sets.
3. Testing: determine usability and functionality of the prototype system and the various modules and make necessary changes to the application.
4. System finalisation and roll out: integrate all the modules of the prototype system and create a suitable graphical user interface.

The theory of groundwater abstraction (see Chapter 2) has been tested extensively through the years and has proven to give accurate results. The data used in this research were obtained from various sources, Geohydrological and Spatial Solutions (GEOSS) and DWAF being the main contributors. The data sets and data types used in the study are based on the specific required outputs of GALET. The outputs have predetermined formats, thus the input

parameters or data sets had to be formatted for optimal processing. The process of constructing a prototype of the system consists of developing separate modules (scripts) in ArcView that would contain algorithms for processing the input data sets and deliver the required output data sets. The implementation of the various algorithms and processing of the data are discussed in further detail in Chapter 3. The prototype construction is followed by the testing thereof (see Chapter 4), which involves checking system outputs resulting from different inputs and changing the algorithms to optimise data processing. The system is then finalised by making it more user-friendly, i.e. refining user control with a graphical user interface (GUI). Chapter 5 will discuss the current value and usability of the developed tool and also look at future developments and recommendations for improvement.

1.7 STUDY AREA

The Sandveld was selected as the study area on the basis of the sensitivity of groundwater resources in the region and the dependency of the local population on groundwater. The Sandveld is an arid stretch of land along the west coast of South Africa (see Figure 1.2). The main towns in the area are Lambert's Bay, Elands Bay, Graafwater, Leipoldtville and Redelinghuys. Land use in the Sandveld is dominated by potato production, an agro-practice that uses large amounts of groundwater in irrigation by pivot sprayers. Additional abstraction is utilised as a municipal water resource for towns.

The study area is of low relief with shallow surface topography gradients along the coast and is bounded in the east by the Uitkomsberge and Zwartberg mountains, which rise to an elevation of approximately 1200 metres above mean sea level. The Sandveld contains various wetland types, including coastal lakes, salt marshes and fynbos (Cowan 1995). The Verlorenvlei wetland system is the best known of the three systems and is a declared Ramsar site. The natural vegetation falls into the Strandveld type and is described as an open semi-succulent scrub of Fynbos intermediate between Coastal Fynbos and Succulent Karoo (Acocks 1988).
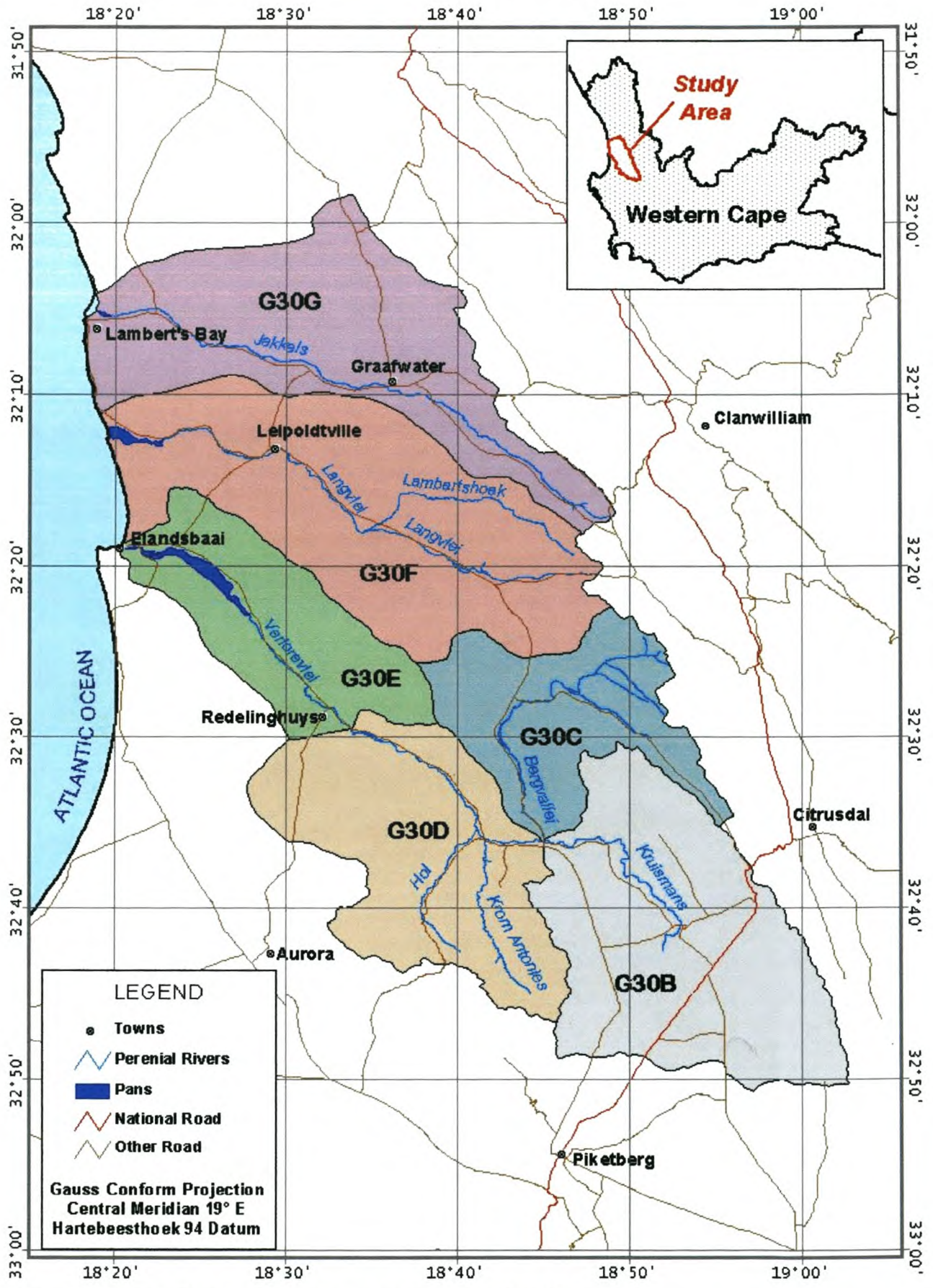
Figure 1.2: Sandveld area along the west coast of South Africa.

The three rivers in the area, Langvlei, Jakkals and Verlorenvlei, are seasonal and interlinked (DWAF 2004). The six main quaternary catchments, as depicted in Figure 1.2, are G30B, G30C, G30D, G30E, G30F and G30G (Harding, Conrad & Low 2003). Groundwater occurrence and characteristics are not confined to surface water catchment boundaries of the area. The catchments of the Sandveld are sensitive, evaporation-driven systems. The annual rainfall is very low (200 mm) and evaporation very high (±1600 mm). The catchments are highly dependent on groundwater, existing as a longitudinal series of wetlands and fed by multiple springs.

The Langvlei catchment (G30F) was chosen as the main focus of this study and testing will be based on the available data for the catchment. Sufficient data are available for this catchment and abstraction in the catchment is intensive. G30F covers an area of 779.9 km^2. The catchment's groundwater resources have been under increasing stress for the past 20 years: 98.6% of groundwater recharge is being abstracted for agriculture, leaving 1.4% for the Groundwater Reserve (Harding, Conrad & Low 2003).

Determination of groundwater levels and impact were achieved by extensive monitoring by the Department of Water Affairs and Forestry and it is clear that there has been a general decline in water levels across the catchment. This is mainly due to over-abstraction for irrigation purposes. These changes are very significant and alarming considering that they have occurred over a period of less than ten years.

The next chapter will discuss the theory and concepts behind groundwater and describe the factors that are of importance when evaluating groundwater resources. In addition the process of groundwater abstraction from a borehole and how to calculate the drawdown is investigated.

CHAPTER 2: GROUNDWATER DRAWDOWN

The abstraction of water from a borehole causes changes in the water table in the vicinity of the point of abstraction. This effect is also called drawdown. Factors such as rate of abstraction and varying geological properties cause variations in drawdown. To understand the groundwater drawdown process, it is necessary to have a basic knowledge of groundwater principles and terminology. This chapter describes groundwater principles and definitions and gives a theoretical layout of the drawdown process and how to estimate drawdown for abstracting boreholes.

2.1 GROUNDWATER

By definition, groundwater is "…water that exists in the pore spaces and fractures in rock and sediment beneath the Earth's surface" (Nelson 2003). It originates as precipitation, and then moves through the soil into the groundwater system, from where it eventually makes its way back to surface streams, lakes, or oceans. Rain that falls on the surface of the Earth seeps down through the soil and into the zone of aeration, undersaturated zone or vadose zone where most of the pore spaces are filled with air. The zone where all the pores and fractures are filled with water is called the saturated zone, as seen in Figure 2.1. The top of the saturated zone is called the water table. The volume of water available depends on the type of soil and rock below the Earth's surface (PADEP 2004). The water table fluctuates in height depending on the topography and climatic conditions such as rainfall and recharge and is usually restricted to depths of 750m and less.

Groundwater makes up only 1% of the Earth's water resources. Economically, groundwater is much cheaper than surface water because it is available at the point of demand at relatively little cost (Thornton, Davison & Lerner 2002). A large portion of the world's drinking and irrigation water is derived from groundwater resources, which causes tremendous pressure in terms of managing the available resource and protecting its quality for continued use. Table 2.1 shows global percentages of the contribution of groundwater to drinking water. In South Africa, it is estimated that groundwater contributes approximately 25% of domestic water use (Kasrils 2000).
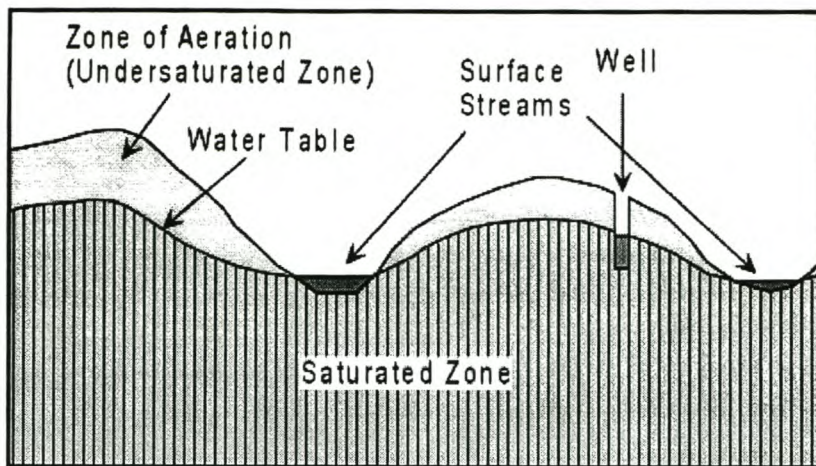
Source: Nelson 2003
Figure 2.1: Various zones forming the groundwater component.

Table 2.1: Global contributions of groundwater to domestic water supplies.

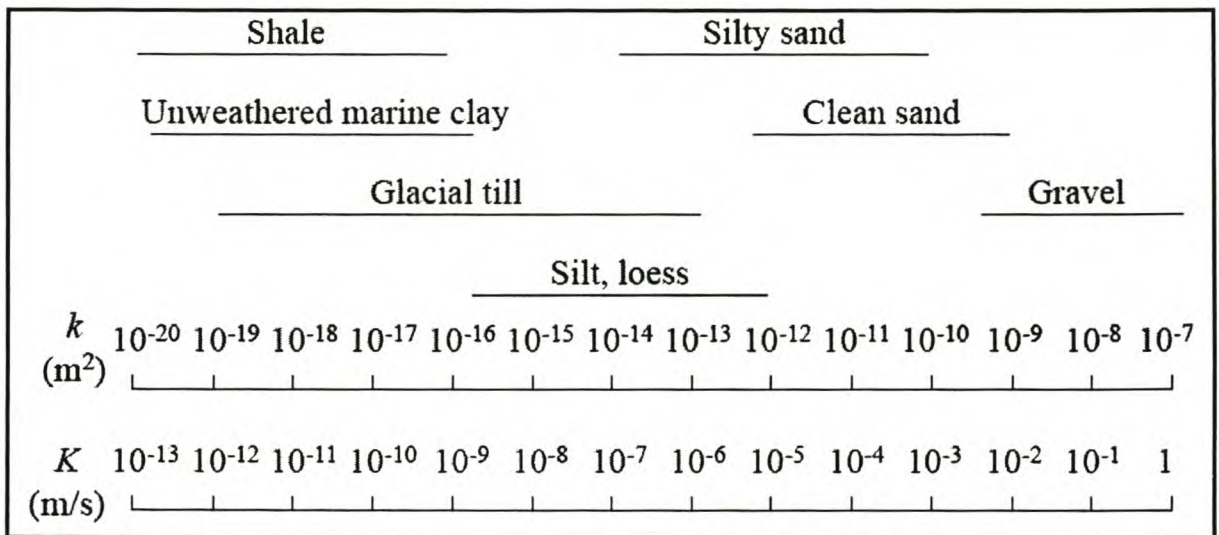| Country	%	Country	%
Australia	14	Malta	100
Austria	97	Netherlands	100
Belgium	64	Norway	5
Canada	14	Poland	50
Cyprus	100	Portugal	49
Czechoslovakia	61	Romania	50
Denmark	98	Spain	30
Finland	52	Sweden	39
France	70	Switzerland	70
Germany	75	Turkey	50
Greece	32	Russia	70
Hungary	78	United Kingdom	35
Ireland	15	United States	45
Luxembourg	71	Yugoslavia	75

Source: Thornton, Davison & Lerner 2002

Groundwater resources are sensitive to pollution and over-abstraction and must be carefully managed. Successful management practices also rely on a firm knowledge of the geohydrological qualities of groundwater resources as discussed on the next section.

2.2 IMPORTANT GEOHYDROLOGICAL CONCEPTS

To maintain sustainable use, it is necessary to identify the distribution and quantity of groundwater in aquifers. An aquifer is saturated subsurface material that yields sufficient water to a borehole. Aquifers can be divided into two broad categories: confined and unconfined. When a geologic unit of lower hydraulic conductivity overlies the aquifer, it is a confined aquifer, while an unconfined aquifer has the water table as its upper boundary (WDNR 1993).

Hydraulic Conductivity, also called the coefficient of permeability, as defined by Parsons (1999, p.3), is "…a measure of the ease with which a fluid will pass through earth material, defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient (in m/d)". The hydraulic conductivity values for a selection of materials are provided in Figure 2.2. Hydraulic conductivity is related to, but not solely determined by, the porosity of the aquifer (Buddemeier & Schloss 2000). All of these characteristics may show considerable variation over a variety of spatial scales.

<table>
<tr><td colspan="2">Shale</td><td colspan="2">Silty sand</td></tr>
<tr><td colspan="2">Unweathered marine clay</td><td colspan="2">Clean sand</td></tr>
<tr><td colspan="2">Glacial till</td><td></td><td>Gravel</td></tr>
<tr><td colspan="4">Silt, loess</td></tr>
</table>

k (m^2) 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7}

K (m/s) 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1

Source: Freeze & Cherry 1979, p.29

Figure 2.2: Range of values of Hydraulic Conductivity (K) and Permeability (k).

Transmissivity is defined as "…the rate at which a volume of water can be transmitted horizontally through a unit width of aquifer under a hydraulic gradient of one (m^2/day)" (Fetter 2001: 100). The transmissivity, as mathematically described in Eq. 2.2, is a product of the hydraulic conductivity (K) and the saturated thickness of the aquifer (b):

$$T = K \times b \quad \text{(Eq. 2.2)}$$

The concept of aquifer transmissivity assumes that flow through the aquifer is horizontal. The borehole depth replaces aquifer thickness to calculate the transmissivity for a specific borehole.

Recharge is the important process of replenishing groundwater. The time movement of infiltrating water is a function of the thickness of the unsaturated zone and the vertical unsaturated hydraulic conductivity. The rate at which water table recharge occurs varies from a few hours in humid areas to years in arid areas (Fetter 2001). As the water infiltrates into the soil, it moves into voids between the aquifer particles that had been filled with air. If the aquifer material is dry, then the rise in the water table from one unit of infiltrated water would be equal to the product of the number of units and the inverse of the porosity of the material. In other words, if the aquifer material has a porosity of 0.25 and 1m of water infiltrates the aquifer, the total rise in the water table will be 4m. It might be more than that due to the occurrence of some water in the material initially (it is not totally dry) and the void ratio might be less than 0.25 (GROW 2004).

The total porosity of a rock is defined as the proportion or percentage (see Eq. 2.1) of a rock or soil that is void of any material, or in other words, the amount of water that the volume of rock can contain (Sloan 2003). In mathematical terms:

$$\text{Total porosity} = \text{Volume of void rock} \div \text{Volume of rock} \qquad (\text{Eq. 2.1})$$

Coarse-textured soil materials such as gravel and sand tend to have a lower total porosity than fine-textured soils such as silts and clays (Freeze & Cherry 1979). Different values for porosity are shown in Table 2.2.

Table 2.2: Porosity values for different mediums.

Medium	Porosity	
	Freeze & Cherry	*Fetter*
Gravel	0.25 – 0.4	0.25 – 0.5
Sand	0.25 – 0.5	0.1 – 0.35
Silt	0.35 – 0.5	0.35 – 0.5
Clay	0.4 – 0.7	0.33 – 0.6

Source: Fetter 2001: 75; Freeze & Cherry 1979: 37

Storativity, or storage coefficient, is "…the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head" (Parsons 1999, p.6).

This is a very important factor in water availability and for calculating the actual volume of groundwater. Storativity is a dimensionless parameter. In confined aquifers, the values range from 0.005 to 0.00005 (Freeze & Cherry 1979).

The next section will discuss the effects of abstracting groundwater from a borehole and how the various factors from this section play a role.

## 2.3 EFFECTS OF A PUMPING BOREHOLE

When a borehole is pumped, the water level drops the most in those soils closest to the borehole and the least in the more distant soils. The soils closest to the borehole would completely dry out if it were not for water being supplied from drainage of these more distant soils to the soils closest to the well (earthDr! 2004). A pumping borehole in an unconfined aquifer tends to create a depression in the water table if water is withdrawn at a rate faster than the aquifer can supply water to the borehole. This decline of the water level, or drawdown, is generally called a cone of depression. The zone of influence (ZOI) refers to the entire area of the water table that is influenced by a pumping borehole or the land area above the cone of depression (see Figure 2.3).

For any aquifer the drawdown cone increases in depth and extent with increasing time (Freeze & Cherry 1979). The shape of the drawdown cone depends on the values for aquifer transmissivity and aquifer storativity, as seen in Figure 2.4. Aquifers of low transmissivity develop tight, deep drawdown cones, whereas aquifers of high transmissivity develop shallow cones of wide extent. Transmissivity exerts a greater influence on drawdown than does storativity.
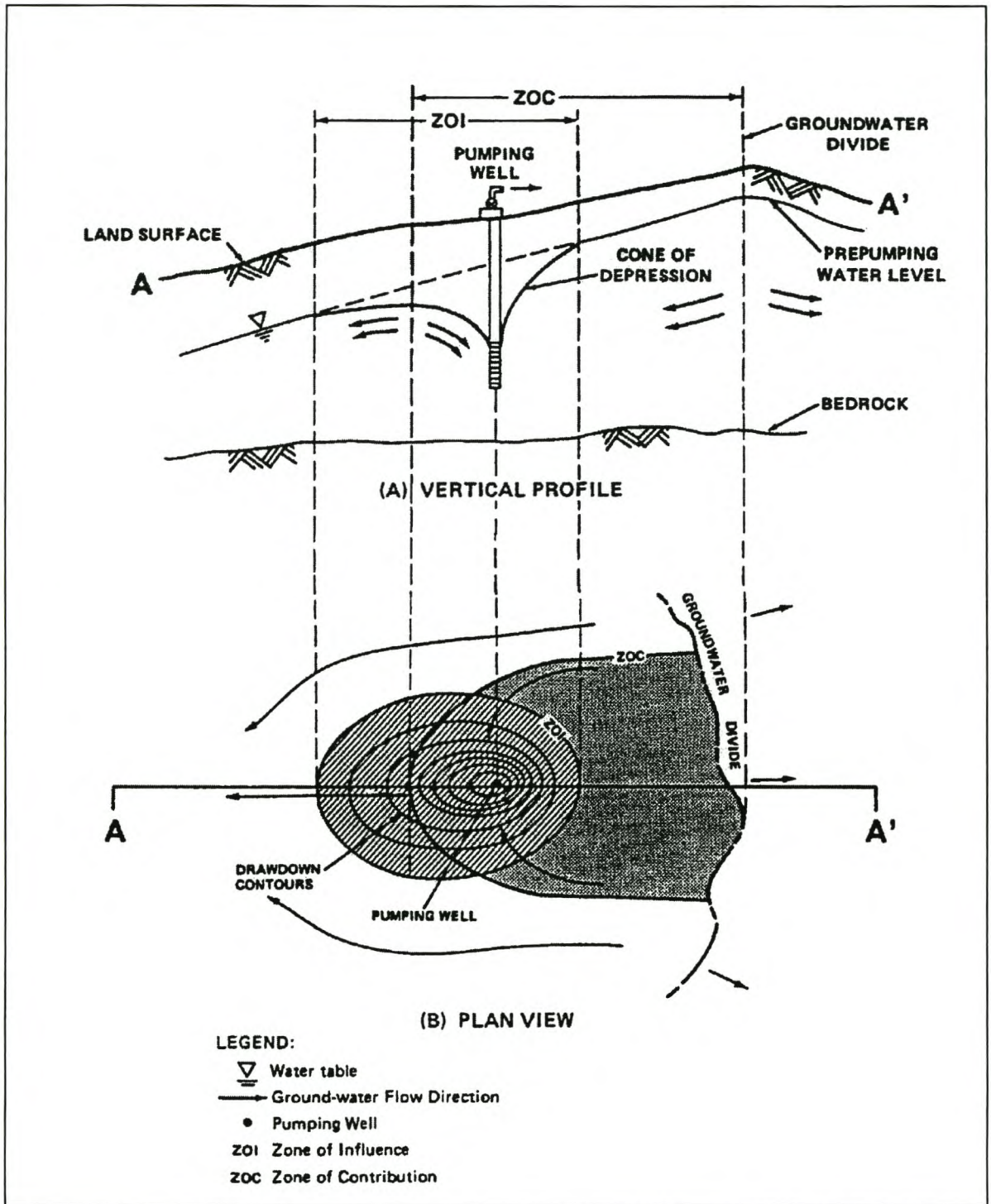
Source: WDNR 1993

Figure 2.3: Cross-section (A) and contours (B) of a hypothetical pumping borehole.
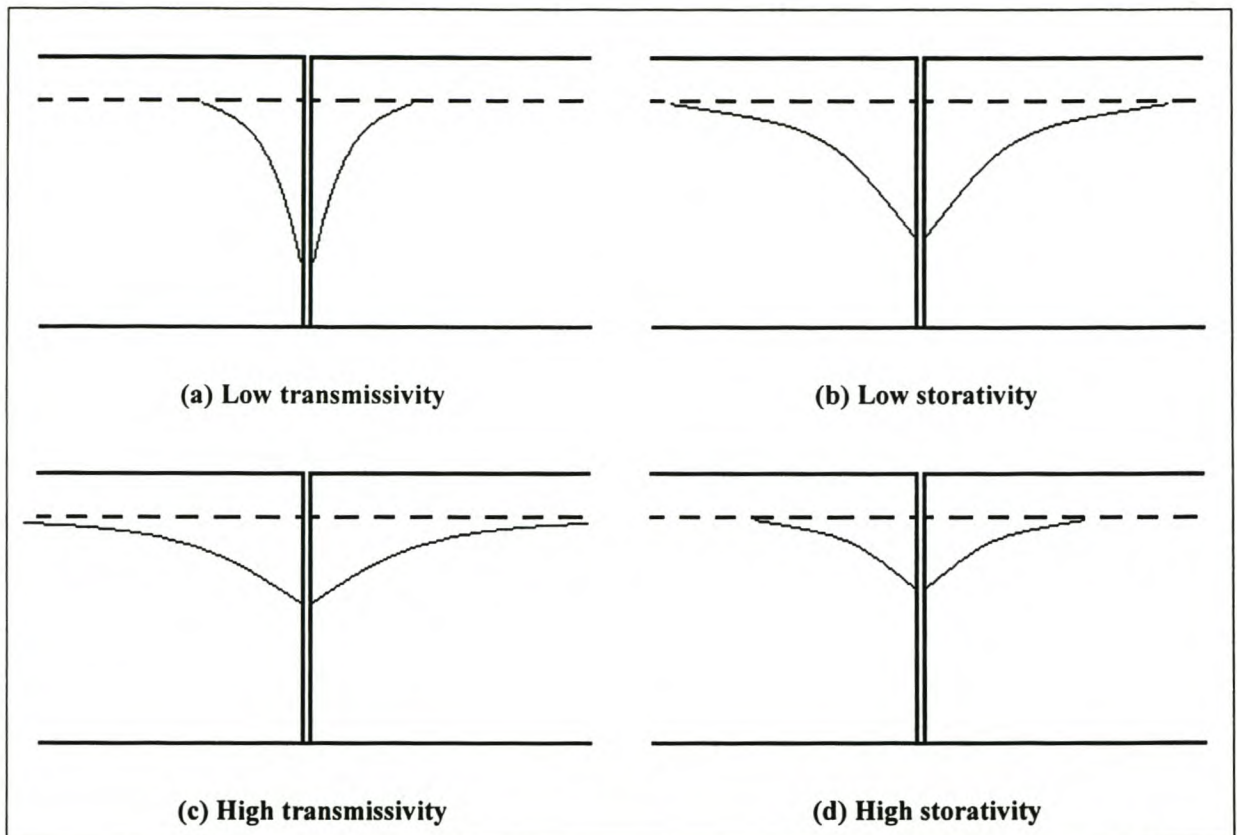
Source: Freeze & Cherry 1979

Figure 2.4: Drawdown cones for aquifers of (a) low transmissivity; (b) high transmissivity; (c) low storativity; (d) high storativity.

2.4 DRAWDOWN CALCULATION

By calculating the cone of depression for a pumping borehole, it is possible to determine the drawdown at specified distances from the borehole. For calculating the drawdown the following assumptions must be made (Fetter 2001; Freeze & Cherry 1979):

- the aquifer is fully penetrated and is homogeneous, isotropic and of constant thickness;
- the aquifer is bounded on the bottom by a confining layer;
- radial symmetry – the values of aquifer transmissivity and storativity do not depend on the direction of flow in the aquifer;
- all flow is radial to the well;
- groundwater flow is horizontal;
- groundwater has a constant density and viscosity;
- the hydraulic head in the aquifer prior to pumping is uniform throughout the aquifer;
- there is only one pumping borehole in the aquifer;
- the pumping rate is constant with time; and
- the diameter of the pumping borehole is infinitesimally small and 100% efficient.

Drawdown at a specified distance from the borehole is based on the equation (see Eq. 2.4) derived by Theis (1935) and is known as the Theis or non-equilibrium equation.

$$h_0 - h = \frac{Q}{4\pi T} \int_u^\infty \frac{e^{-a}}{a} \, da \qquad \text{(Eq. 2.4)}$$

where $Q \Rightarrow$ the constant pumping rate (L/s; m^3/day);

$h \Rightarrow$ the hydraulic head or water level (meters);

$h_0 \Rightarrow$ the initial hydraulic head or water level (meters); and

$T \Rightarrow$ the aquifer transmissivity.

The integral in the Theis equation is written as $W(u)$ (see Eq. 2.5) and is known as the exponential integral, or well function, which can be expanded as infinite series:

$$W(u) = -0.5772 - \ln u + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \dots \qquad \text{(Eq. 2.5)}$$

where the argument u is given by

$$u = \frac{r^2 S}{4Tt} \qquad \text{(Eq. 2.6)}$$

where r $\Rightarrow$ the radial distance from the pumping borehole;

$S \Rightarrow$ the aquifer storativity;

$T \Rightarrow$ the aquifer transmissivity; and

t $\Rightarrow$ the time since pumping began.

Thus the final equation (Eq. 2.7) for calculating the drawdown (d) at a specified radial distance from a pumping borehole would be:

$$d = \frac{Q}{4\pi T} W(u) \qquad \text{(Eq. 2.7)}$$

The example on page 17 (from Fetter 2001) shows how to calculate the drawdown at a specified radial distance from a pumping borehole. The example can be repeated for several radial distances away from the pumping borehole and also for longer periods of abstraction. A representation of the drawdown effect, with a hypothetical flat initial water table and a homogeneous and isotropic aquifer, can be seen in Figure 2.5. Drawdown values at various distances from a pumping borehole are shown in Table 2.3.

A borehole, 20.1m deep, is pumping at 2725 m^3/day for 1 day. The aquifer has a storativity of 0.0051 and a hydraulic conductivity of 14.9 m/day. The drawdown 7.0 m from the borehole, after the pumping period of one day is:

Parameters: Q = 2725 m^3/day

S = 0.0051

K = 14.9 m/day

b = 20.1 m

$\therefore T = b \times K = 299$ m^2/day

$$u = \frac{r^2 S}{4Tt} = \frac{10^2 \times 0.005}{4 \times 1000 \times 10} = 0.00021 = 2 \times 10^{-4}$$

$$W(u) = 7.94$$

$$\therefore d = \frac{2725}{4\pi \times 299} \times 7.94 = 5.76m$$

Thus the drawdown is 5.76 m at a distance of 7 meters from the borehole after pumping for 1 day at 2725 m^3/day.
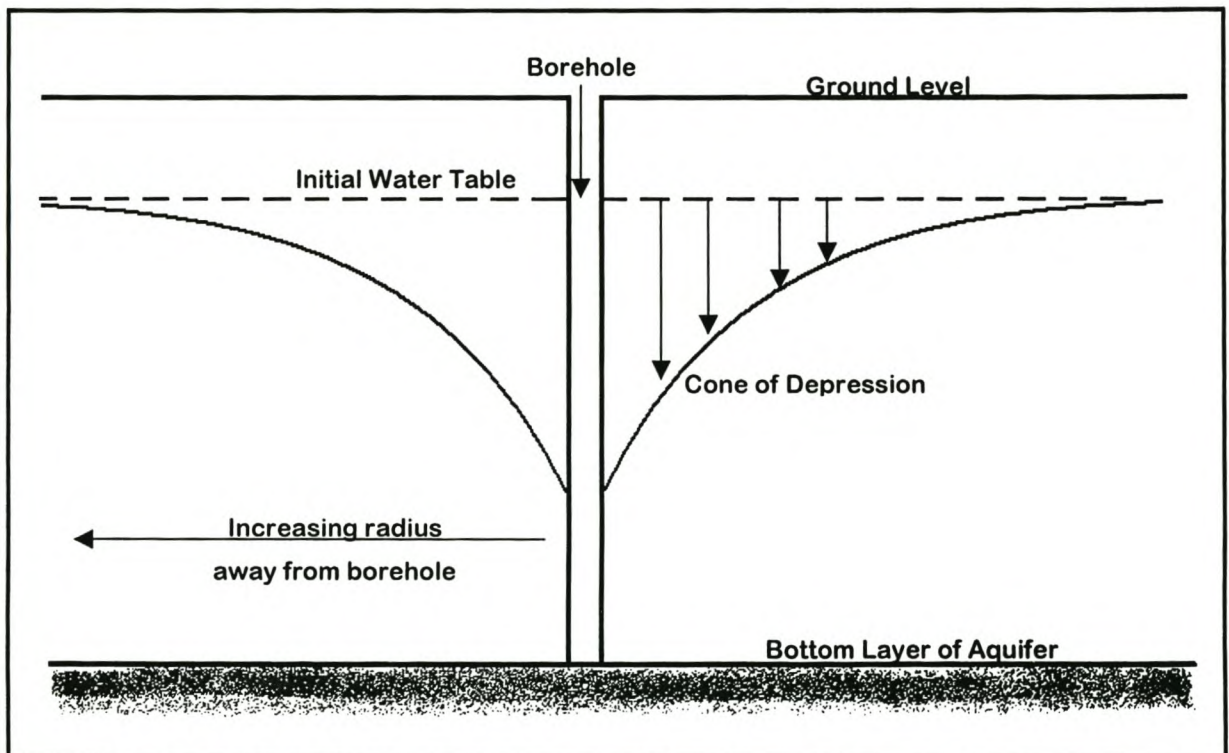

Figure 2.5: Cone of depression as developed from the drawdown of a pumping borehole.

Table 2.3: Example of drawdown values at various distances from a pumping borehole.

r (m)	u	W(u)	Drawdown (m)
1.5	5.17×10^{-4}	7.0	4.1
5.5	6.96×10^{-3}	4.4	2.6
10	2.30×10^{-2}	3.2	1.9
25	1.44×10^{-1}	1.5	0.89
75	1.29	0.17	0.10
150	5.18	0.0017	0.0010

Source: Fetter 2001

Using the example by Fetter (2001), namely the drawdown at the specified point for a month (31 days), a significant drop in the water level can be observed. Figure 2.6 shows the daily decline in the water table at a distance of seven metres from the borehole. The water level after 31 days is 8.2 metres below ground level, thus a total drop of approximately 2.5 metres.
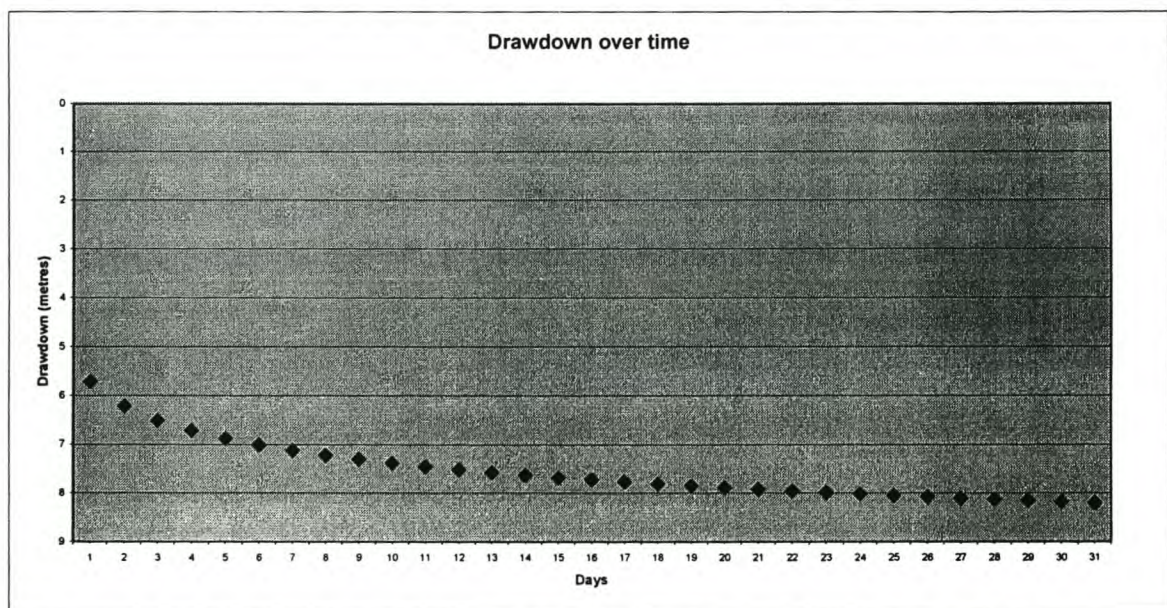

Figure 2.6: Example of drawdown seven metres from borehole over a period of one month.

To determine the full effect of the abstraction from the borehole, the area over which drawdown occurs must be calculated. The next section describes the method for calculating the zone of influence of an abstracting borehole.

2.5 CALCULATING THE ZONE OF INFLUENCE (ZOI)

As mentioned in section 2.3, the ZOI refers to the entire area of the water table that is influenced by a pumping borehole or the land area above the cone of depression. A protection area is needed to provide a safe buffer zone defined as the distance from the borehole to which abstraction may take place within a specified period of time.

The Cooper-Jacob method is a simplified adaptation of the Theis method. From the Cooper-Jacob method, storativity can be computed as a function of transmissivity, time, and the value of the intercept at the point of zero drawdown as seen in Eq. 2.8 (USACE 1999).

$$S = \frac{2.25Tt}{r_0^2} \quad \text{(Eq. 2.8)}$$

where S => aquifer Storativity;

      T => aquifer Transmissivity;

      t => time at which drawdown is measured; and

      r_0 => radius of influence.

With the known value for aquifer storativity, Eq. 2.8 can be rearranged to Eq. 2.9 to indicate the ZOI or distance from the point of abstraction at which the drawdown will be zero over a period t:

$$r_0 = 1.5\sqrt{\frac{Tt}{S}} \quad \text{(Eq. 2.9)}$$

The Cooper-Jacob method can be used to calculate the ZOI for an abstracting borehole, but it does not use the rate of abstraction as a parameter. The ZOI will therefore be independent of the rate of abstraction. This method yields results that show the calculated ZOI to be too large to be realistic and will not be considered as the preferred method to be used in GALET.

The Calculated Fixed Radius (CFR) method can be used to calculate the zone of contribution (ZOC) for an abstracting borehole (WDNR 1993). The radius for the ZOC is calculated as:

$$r = \sqrt{\frac{Qt}{\pi Hn}} \quad \text{(Eq. 2.10)}$$

where Q => rate of abstraction;

      t => period of abstraction;

      H => depth of borehole; and

   n => aquifer porosity.

The CFR method is dependent on accurate porosity values and is used to determine the extent of groundwater pollution and the actual movement of groundwater. The ZOC, as calculated with the CFR method, can be too small to serve as a safe zone around the borehole. Therefore the CFR method will not be used in GALET.

The method that will be used in GALET to calculate the ZOI is based on the rate of abstraction and a drawdown threshold. A threshold of zero meters of drawdown will yield a very large ZOI. A threshold minimum of 0.1 and a maximum of 0.5 should be used to determine the ZOI. A smaller threshold value can be used in ecologically sensitive areas, e.g. in the vicinity of wetlands, where a small change in the groundwater level can have a great impact. A larger threshold value can be used in areas that are ecologically unimportant, e.g. large farming areas. GALET will calculate the distance from the borehole at which the drawdown reaches the specified threshold after a given period of abstraction. This distance will be set as the radius of the ZOI for the specified abstraction period and rate. This method is more flexible than the Cooper-Jacob method and can give more realistic results.

2.6 MULTIPLE DRAWDOWN

When multiple boreholes are withdrawing from an aquifer, the total drawdown will be the sum of the drawdown for each of the individual boreholes (see Figure 2.7). An arithmetic summation of the Theis equation can be used to calculate the total drawdown at any given point at a radial distance r from the borehole.
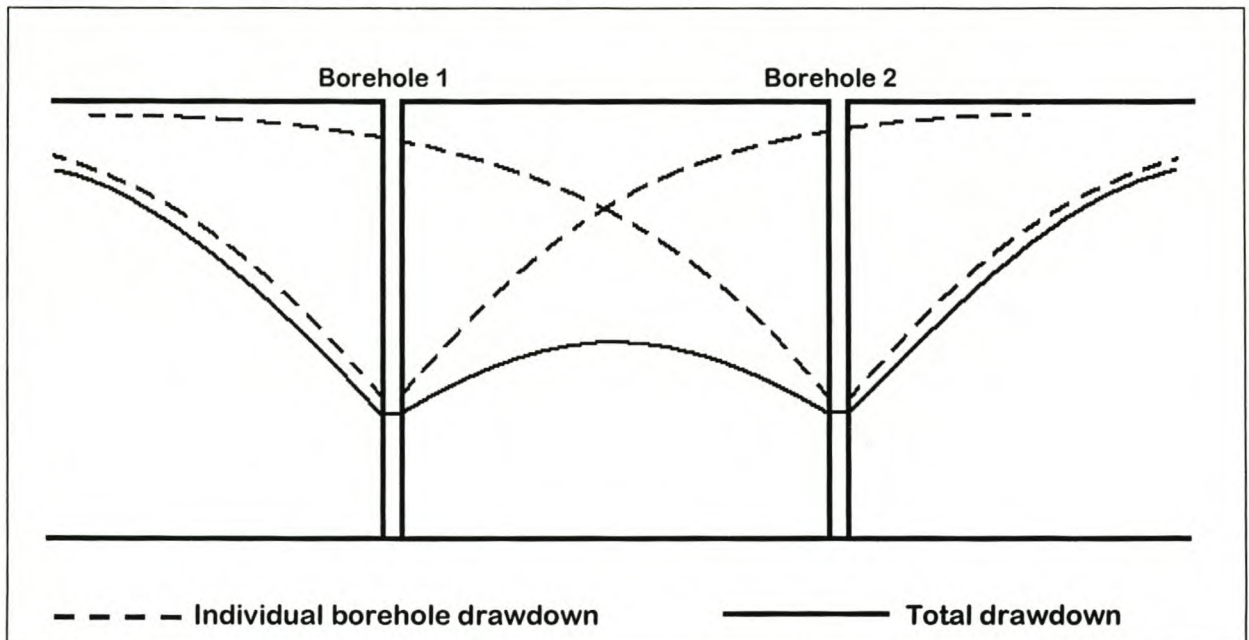
Source: Freeze & Cherry 1979

Figure 2.7: Drawdown by multiple boreholes.

If there is a recharging borehole (adding water to the groundwater) in the aquifer system, the effect will be the exact opposite. The total drawdown can be calculated by finding the difference between the abstracting and recharging boreholes, using the Theis equation.

2.7 DRAWDOWN WITH A SLOPING WATER TABLE

When the water table is not flat, the effect of the drawdown will vary with the angle of the water table. Figure 2.8 shows the cone of depression with a flat water table (solid line) and the cone of depression of a sloping water table (dotted line).
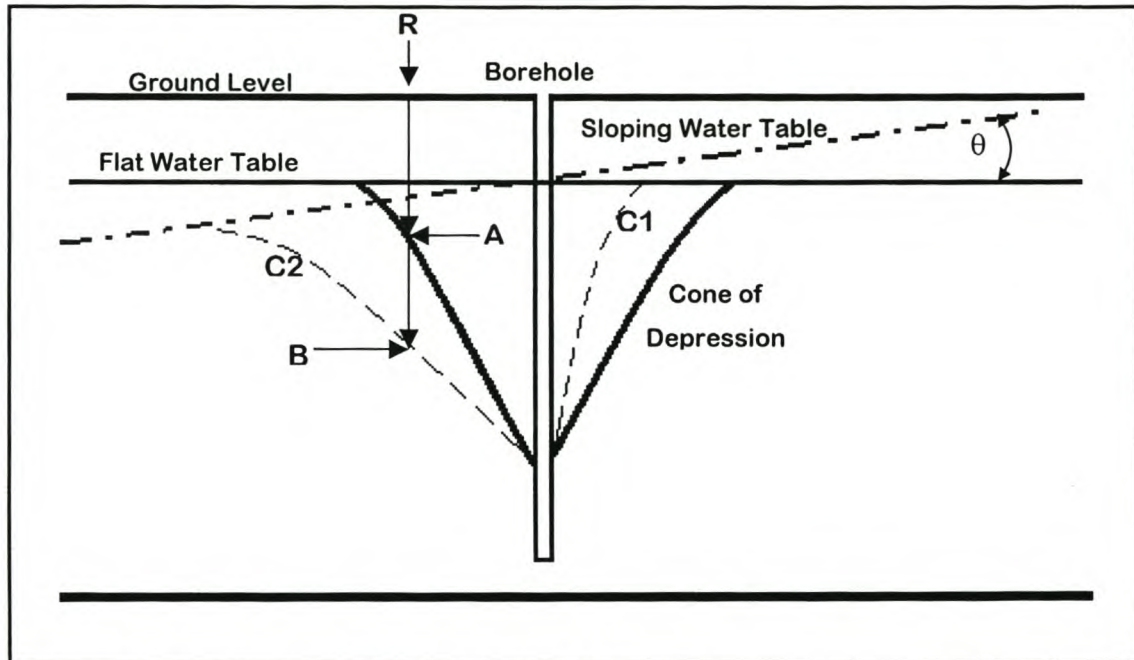

Figure 2.8: Drawdown with a sloping water table.

If the water table is sloping up as the radial distance R increases away from the borehole, the drawdown curve will be steeper, as seen at point C1 in Figure 2.8. A water table that slopes down as the radial distance R increases away from the borehole will produce a flatter drawdown curve as seen at point C2 in Figure 2.8. According to Van Tonder (2004, pers com), the drawdown cone will always be a perfect circle around the pumping borehole if the water table is flat, but the contours generated from the water levels will be asymmetrical (assuming that the aquifer is homogeneous and isotropic), depending on the slope of the water table. The drawdown cone will also be a perfect circle if no boundaries are reached and this assumption will be used in GALET. This effect is also visible in Figure 2.3 (A).

The first step in calculating the drawdown for a borehole with an angling water table is to calculate the drawdown cone of depression for a hypothetical flat water table for the borehole. The next step is to calculate the difference (drop or rise) in the water table if an angle is introduced. The difference is then added (for a down-slope) or subtracted (for an up-slope) to the drawdown depth of the flat water table to produce the final water table depth.

The effect of a sloping water table can be seen in Figure 2.8, where **R** is any radial distance from the borehole, point **A** is the water level after pumping with a flat water table, and point **B** is the water level after pumping under the same conditions, but with a sloping water table. Thus the result of a sloping water table can be significant.

To calculate the difference in water levels between a flat and a sloping water table, simple trigonometry can be used. When calculated over a distance unit *u* (see Figure 2.9), the difference in drawdown can be described as:

$$du = \tfrac{1}{2}\,u \tan \theta \quad \text{(Eq. 2.11)}$$

where

       u => distance unit

       θ => angle of water table

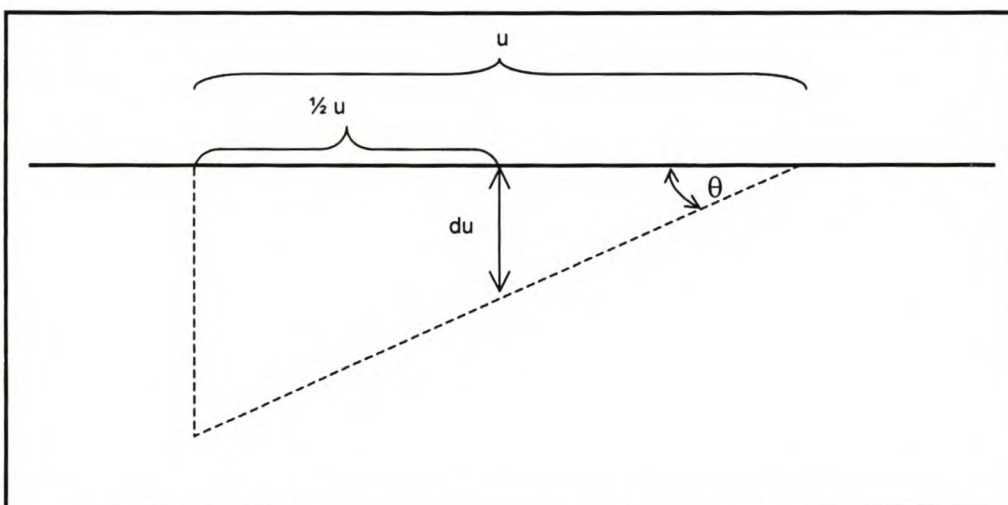   *du* => difference in water level calculated at distance ½ *u*

Figure 2.9: Difference in drawdown du as calculated over a unit distance u.

In ArcView, a grid best represents the drawdown for a borehole. A distance unit *u* defines the grid cell size and the drawdown is calculated per cell from the borehole to the outer extent of the ZOI. Thus, ½ *u* defines the centre of the grid cell and the drawdown and effect of the water table slope are calculated at that point.

This chapter discussed groundwater principles and definitions and gave a theoretical layout of the drawdown process and how to estimate drawdown for abstracting boreholes. In the next chapter this theory is implemented in ArcView to determine drawdown levels for pumping boreholes under various conditions.

CHAPTER 3: GALET IMPLEMENTATION

This chapter describes how the theory of groundwater drawdown, as discussed in Chapter 2, is implemented in GALET to determine drawdown levels for pumping boreholes under various conditions. This chapter gives a full description of the data sets that are used in the system and how the data sets are implemented. The later sections present an overview of the various system modules that are used for the to do drawdown calculations.

3.1 USER REQUIREMENTS STUDY

A user requirements study was done to determine the various functions of GALET. The user requirements study involved interviews with DWAF staff members from the Bellville regional office and the Pretoria national office. Mr Bayanda Zenzile, the person in charge of water usage evaluation and registration in the Western Cape, was a key role player in determining the required functions for the tool (Zenzile 2004, pers com). The current process of registering and licensing groundwater usage within DWAF was assessed as part of the user requirements study. The focus point was to minimise the time spent on field investigations appraising the impact of groundwater abstraction and to create a similar, more streamlined evaluation process in a desktop environment. It was decided that the desktop evaluation should include the following functions:

- add a new borehole with abstraction details similar to the official DWAF water use registration forms (see Appendix A);
- modify borehole information to simulate changing conditions;
- calculate the drawdown in the groundwater table;
- calculate the zone of influence (ZOI);
- determine the potential impact on sensitive features like rivers and wetlands; and
- summarise the evaluation in a report.

The functions of the system determined which data sets would be used. The required data components are discussed in the next section.

3.2 DATA COMPONENTS

The process of calculating the drawdown for a borehole requires various parameters and inputs from a broad spectrum of data sources. Table 3.1 describes these parameters and the required format of each data set.

Table 3.1: Data sources required for calculating the drawdown of a pumping borehole.

Type	Format	Description
Borehole	Point	Point consisting of *x,y* coordinates (decimal degrees) that represents a point of abstraction on the surface. *Source*: user input
Geology	Polygon	Layer with various lithology descriptions that link to other parameters such as hydraulic conductivity, transmissivity and storativity. *Source*: DWAF
Recharge	Polygon	Layer describing recharge. *Unit*: mm/annum *Source*: DWAF
Rainfall	Polygon	Layer describing rainfall. *Unit*: mm/annum *Source*: DWAF
Porosity	Grid	Grid of the porosity values. *Unit*: dimensionless *Source*: DWAF
Effective Recharge	Grid	Grid of effective recharge values as calculated using appropriate Recharge and Porosity values. *Unit*: mm/annum
Initial Water Table	Grid	Grid of water levels before any drawdowns have been calculated. The standard resolution is 50m. *Unit*: mbgl [meters below ground level] *Source*: DWAF
Water Table Slope	Grid	Grid of the initial water table slope as derived from the Initial Water Table Grid. *Unit*: degrees [slope]
Water Table Aspect	Grid	Grid of the initial water table aspect as derived from the Initial Water Table Grid. *Unit*: degrees [direction]

Based on the required functions of the system, the majority of the data components were determined before programme construction was initiated (see section 3.1). The next section deals with the construction process.

3.3 CONSTRUCTION

GALET was constructed in ESRI's ArcView GIS 3.2. The Avenue scripts are available on the compact disc (Appendix C). The main reason for using ArcView was that DWAF (the end user) is currently using it as their main GIS software package and therefore would not need to purchase any additional software to run the system. This will keep costs down and allow for easy modifications in the future. In addition, very little training will be necessary, as the operators have a good knowledge of the software.

ArcView is also an ideal platform for GALET as it is capable of executing the operations and calculations required to determine drawdown at a spatial level and has additional powerful features such as (Jewitt et al 1998):

- a user-friendly Graphical User Interface (GUI);
- a wide range of graphic capabilities;
- vector and grid capabilities which allow accurate calculations;
- various modelling tools;
- a scripting language (AVENUE) to customise the working environment;
- tools to link to external applications and databases; and
- comprehensive database capabilities.

The above-mentioned features can be integrated to create a function-specific tool within ArcView to assist in the process of evaluating drawdowns of pumping boreholes.

A key requirement of the system is that it is able to cater for user inputs. Like the current water use registration forms (see Appendix A), a user must be able to specify the position of new boreholes by entering coordinates, as well as abstraction rates, drilling depths and drilling periods for each borehole. Experts must also be able to exercise the option of entering more accurate values for transmissivity, storativity, porosity and recharge for a specific borehole or aquifer.

The next section will explain how the various factors were taken into consideration and integrated in the process of calculating the drawdown.

3.4 DRAWDOWN

When a new borehole is created in the Borehole layer, the drawdown has to be calculated for a specified abstraction rate and period of abstraction. The scripts that are used for calculating the drawdown are described in Appendix B. Here follows a step-wise description of this process as it is implemented in GALET:

Step 1: The drawdown is calculated as for a flat water table. The extent of the cone of depression is calculated with Eq. 2.9 (Section 2.5). The drawdown is calculated at 10m intervals from the outer edge of the cone of depression inward up to the edge of the borehole shaft. The intervals are set at 10m to simplify the grid operations. The standard borehole shaft width is accepted as 0.16m, thus the edge of the shaft will be at a radius of 0.08m. If the

drawdown is calculated at the centre of the borehole with the Theis equation (Eq. 2.7, Section 2.4), the result will be infinity. Therefore the drawdown is calculated only up to the edge of the borehole shaft. The drawdown values for the selected borehole are represented as concentric circles in a polyline theme.

Step 2: The drawdown circles are converted to a grid theme (see Figure 3.1). This grid represents the drawdown with a flat water table with a resolution of 10m. All grid cells outside the extent of the cone of depression are given a 'NO DATA' value.
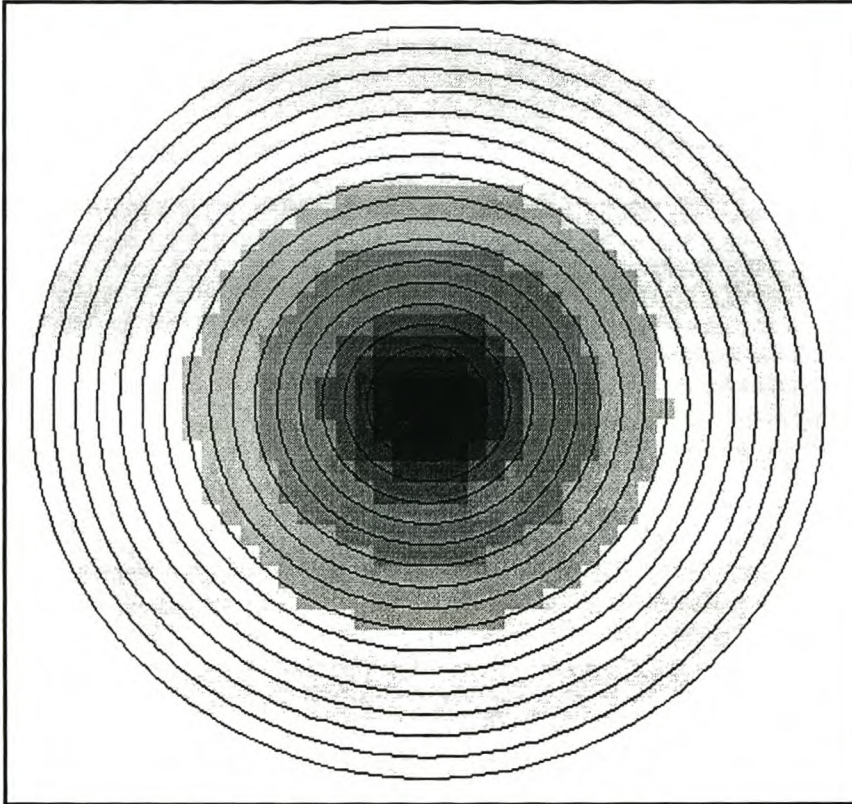

Figure 3.1: Drawdown grid as created from the drawdown circles.

Step 3: Sectors are created for the 8 main directions, as specified in Table 3.2, to select the cells from the Water Table Aspect grid. The sectors are buffered by half a cell size (ESRI Online Support Centre 2000) to ensure that an adequate number of grid cells are selected to fully cover each sector (see Figure 3.2).

Table 3.2: Values for 8 main direction sectors.

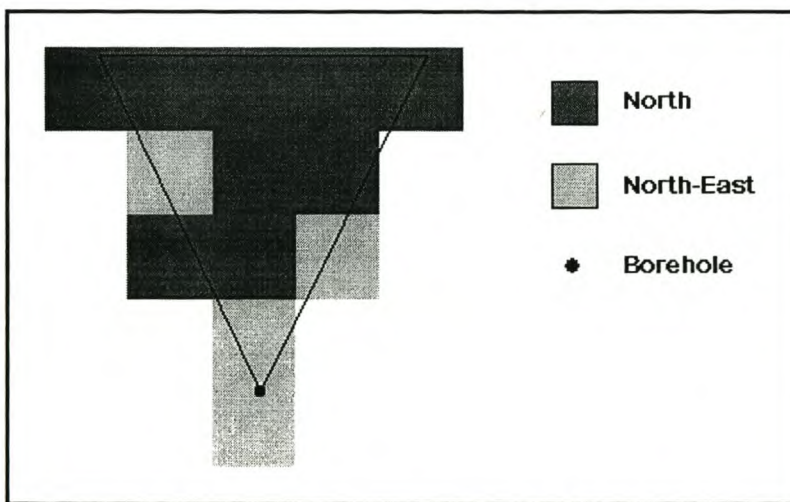| Direction	Value (degrees)
North	0 - 22.5; 337.5 - 360
North-East	22.5 - 67.5
East	67.5 - 112.5
South-East	112.5 - 157.5
South	157.5 - 202.5
South-West	202.5 - 247.5
West	247.5 - 292.5
North-West	292.5 - 337.5

Figure 3.2: The northern sector as generated for the relative aspect grid.

Step 4: The selected cells are then converted per direction sector to create a relative water table slope aspect grid with a resolution of 50m. This process is necessary to determine if the water table is sloping away or towards the observation point or borehole. The relative water table is then used to calculate the cone of depression as explained in section 2.7.

For example, take north (or 0°) as the main direction to which the other directions will be seen to be relative. If one is facing north (0°), then a north-facing slope can be seen as sloping away from the observer and a south-facing slope (180° aspect) is sloping towards the observer. If one is facing south (180°), as the viewing direction from A to B in Figure 3.3 indicates, a south-facing slope would be seen as sloping away from the observer (relatively 0°) and a true north-facing slope as sloping towards the observer (relatively 180°) (see Figure 3.4). In Figure 3.3 the sectors on the inside of the circle represent the viewing directions and

the directions on the outside indicate the newly assigned relative aspect for each viewing direction.
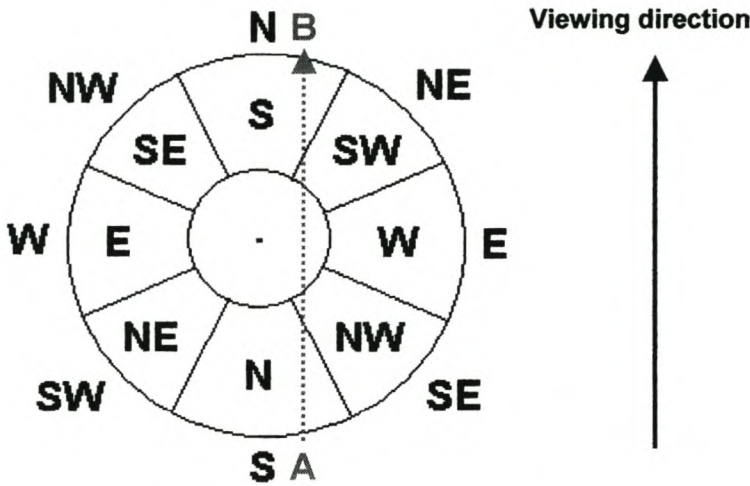

Figure 3.3: Relative aspect slopes when viewing south (A to B).

The cross-section of the viewing direction A to B, where the true south-facing slope now represents a relative 0° aspect slope and the true north-facing slope represents a relative 180° aspect slope, is indicated in Figure 3.4. The other slopes on the grid are also converted to relative aspect slopes as in Figure 3.3.
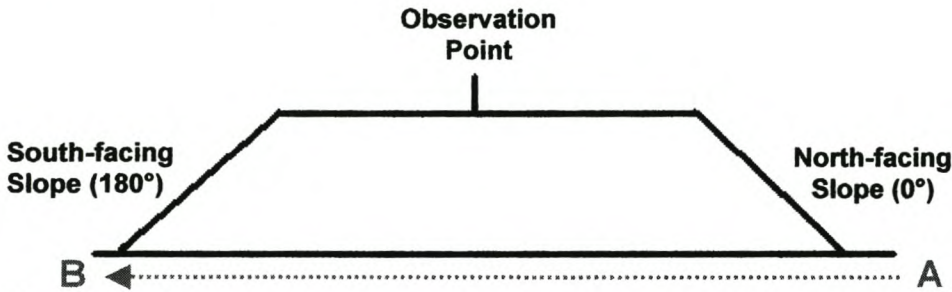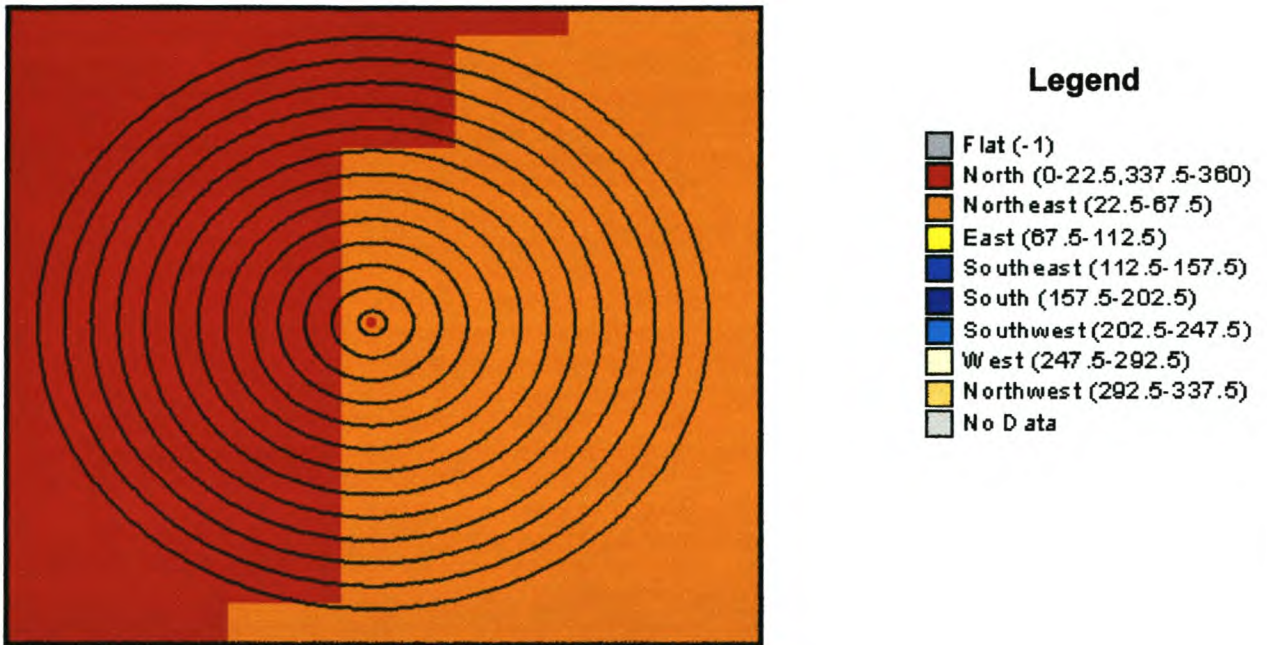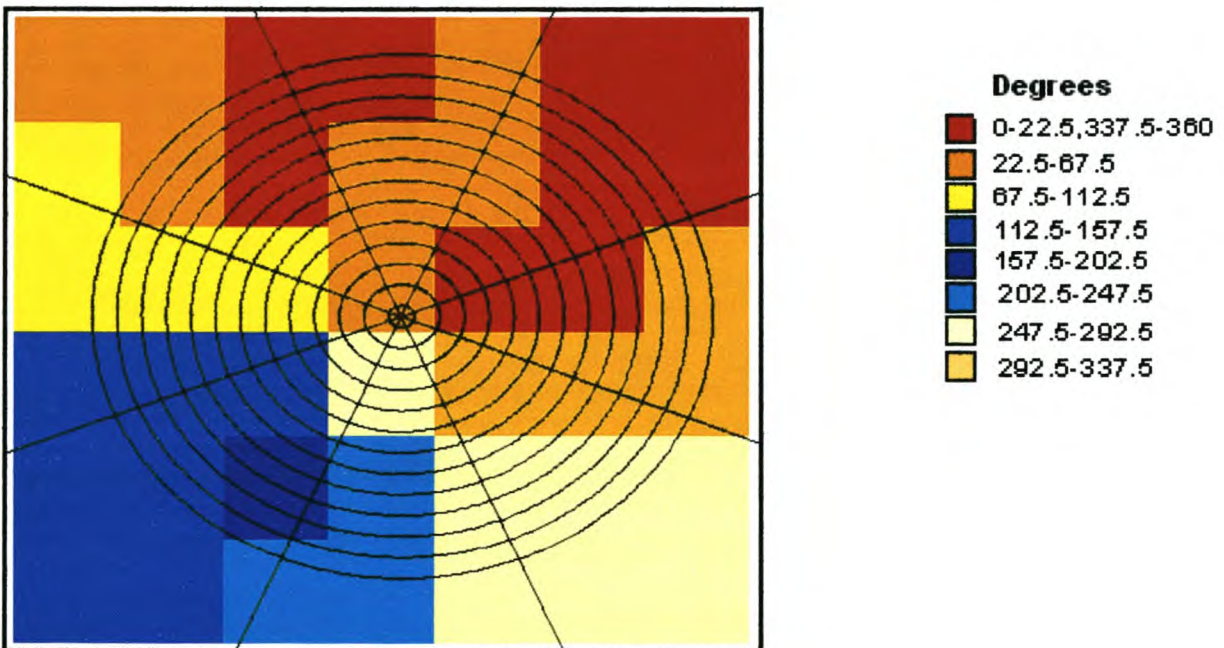

Figure 3.4: Cross-section of viewing direction A to B in Figure 3.3.

After the relative aspect grid has been calculated for each of the main direction sectors, the different sectors are combined to create the final relative aspect grid (see Figure 3.5).

(a) Aspect grid over drawdown area.

Legend

- ◻ Flat (-1)
- ◼ North (0-22.5,337.5-360)
- ◼ Northeast (22.5-67.5)
- ◻ East (67.5-112.5)
- ◼ Southeast (112.5-157.5)
- ◼ South (157.5-202.5)
- ◼ Southwest (202.5-247.5)
- ◻ West (247.5-292.5)
- ◻ Northwest (292.5-337.5)
- ◻ No Data

(b) Relative aspect grid over drawdown area.

Degrees

- ◼ 0-22.5,337.5-360
- ◼ 22.5-67.5
- ◻ 67.5-112.5
- ◼ 112.5-157.5
- ◼ 157.5-202.5
- ◼ 202.5-247.5
- ◻ 247.5-292.5
- ◻ 292.5-337.5

Figure 3.5: Result of converting (a) the aspect grid to (b) a relative aspect grid per sector.

Step 5: The Water Table Slope grid is now combined with the relative aspect grid from *Step 4*. This produces a grid containing values for relative slope and angle of slope for the water table. Cells that are perpendicular to the line of sight from the borehole (0° and 180° relative aspect) and have the same or directly opposite aspect as the viewing direction, will keep their original slope gradient. For instance, if one is looking north (0°) at a cell with a 0° or 180° aspect, the cell will keep its original gradient. However, if one is looking at a cell with an

aspect perpendicular to the viewing direction (90° or 270° relative aspect), the gradient across the cell cannot be the same as the original gradient. An example of this situation would be if one were looking north (0°) at a cell with an easterly aspect (relative 90° aspect). In this case the gradient across the cell can be calculated using trigonometry.
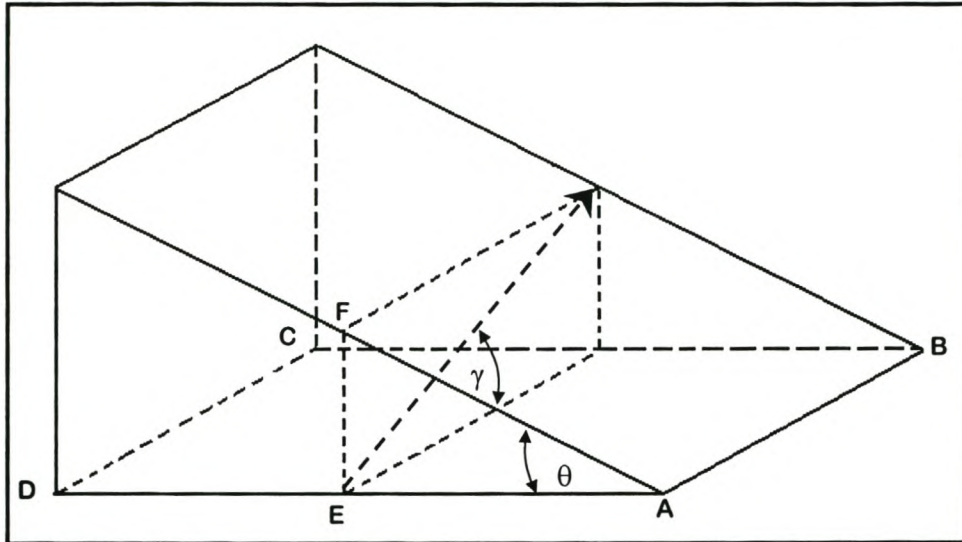

Figure 3.6: 3-dimensional view of a section of a sloping water table with a relative 90° aspect as represented by a grid cell in ArcView.

From Figure 3.6, let ABCD be the grid cell base and θ the gradient of the water table. The viewing direction is from A to B. AD (= AB) is the width of the grid cell. Then:

$$\text{AE} = \frac{AD}{2} = \frac{AB}{2} \qquad \Rightarrow \text{ centre of grid cell (Eq. 3.1)}$$

$$\text{EF} = \text{AE} \tan\theta \qquad \Rightarrow \text{ change in height over the grid cell (Eq. 3.2)}$$

$$\tan\gamma = \frac{EF}{AB} \qquad \Rightarrow \text{Eq. 3.3}$$

$$= \frac{AE \tan\theta}{AB}$$

$$= \frac{(AB/2)\tan\theta}{AB}$$

$$= \tan\theta / 2 \frac{\tan\theta}{2}$$

$$\therefore \gamma = \tan^{-1}\frac{\tan\theta}{2}$$

$$= \frac{\theta}{2} \qquad \Rightarrow \text{ new gradient of the water table}$$

Instead of calculating the effect of a sloping water table with a gradient of θ, an angle of $\theta/2$ is used when the cell aspect is perpendicular to the viewing direction. A similar modification is made when the viewing line crosses the grid cells at a non-perpendicular angle. An example of this would be if one were looking in a direction of $0°$ at a cell with a $125°$ relative aspect as in Figure 3.7. Let ABCD be the grid cell base and θ the gradient of the water table. The viewing direction is from A to C. Then:

$$AD = AB \qquad\qquad \text{=> grid cell width (Eq. 3.4)}$$
$$DF = AD \tan\theta = CE \qquad \text{=> change in height over the grid cell (Eq. 3.5)}$$
$$AC = \sqrt{AD^2 + AD^2}$$
$$ = \sqrt{2AD^2}$$
$$ = AD\sqrt{2}$$

$$\tan\gamma = \frac{CE}{AC} \qquad\qquad \text{=> Eq. 3.6}$$
$$ = \frac{AD\tan\theta}{AD\sqrt{2}}$$
$$ = \frac{\tan\theta}{\sqrt{2}}$$
$$\therefore \gamma = \tan^{-1}\frac{\tan\theta}{\sqrt{2}}$$
$$ = \frac{\theta}{\sqrt{2}} \qquad\qquad \text{=> new gradient of the water table}$$
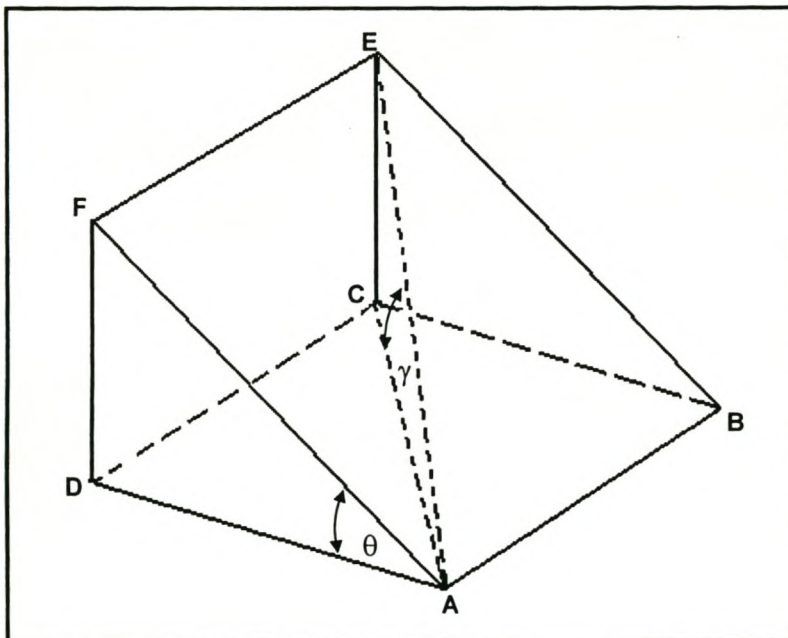

Figure 3.7: 3-dimensional view of a section of a sloping water table with a 125° relative aspect (south-east) as represented by a grid cell in ArcView.

Step 6: The drawdown grid from *Step 2* is now combined with the result from *Step 5*. The effect of the drawdown with a sloping water table can now be calculated.

Step 7: The final step is to add the result of *Step 6* to the original water table grid to create a new water table grid that includes the effect of drawdown of the abstracting borehole. The contours generated for a sloping water table would not be symmetrical circles, but asymmetrical (see Figure 3.8) and slightly shifted from the centre of the borehole, depending on the dominant water table slope direction.
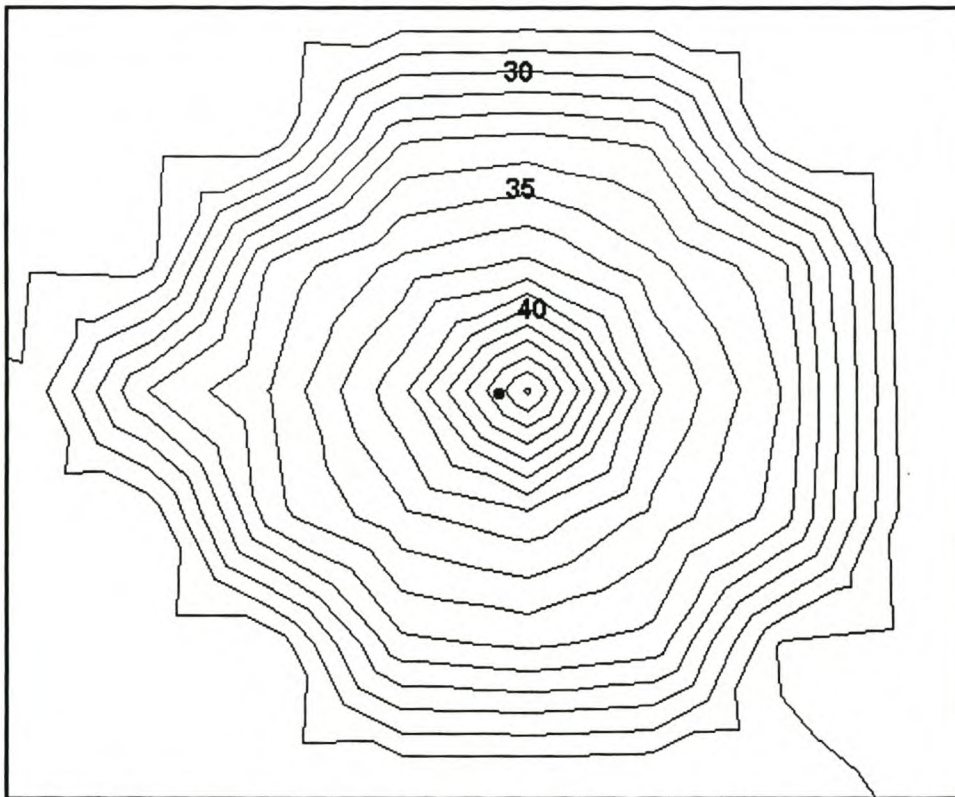

Figure 3.8: The drawdown contours for a pumping borehole with a sloping water table.

The next section explains the procedure for calculating the drawdown when multiple boreholes are contributing to groundwater abstraction.

3.5 MULTIPLE BOREHOLES

When the zones of influence (ZOI) of neighbouring boreholes or abstraction points overlap, the resulting drawdown of the overlapping zones will be the collective sum of the individual drawdowns (see section 2.6).

For multiple boreholes, the first step is to calculate the drawdown grid for the first borehole, following steps 1-7 as described in section 3.3 (see Figure 3.9 (a)). The same process is followed for calculating the drawdown for a second borehole, but the drawdown grid for the second borehole is now added to the water table grid showing the effect of drawdown of the first borehole (see Figure 3.9 (b)), where the red circles around the points indicate the ZOI for each of the boreholes and the grey contours of the water table grid is displayed and labelled as metres below ground level (mbgl).

The different functions described in this chapter form the core function of GALET. The functions can be applied for different scenarios e.g. single and multiple boreholes. In the next chapter the capabilities of the system are demonstrated and results from test data sets presented. Chapter 4 also contains screen shots and describes how the various input dialog boxes are used.
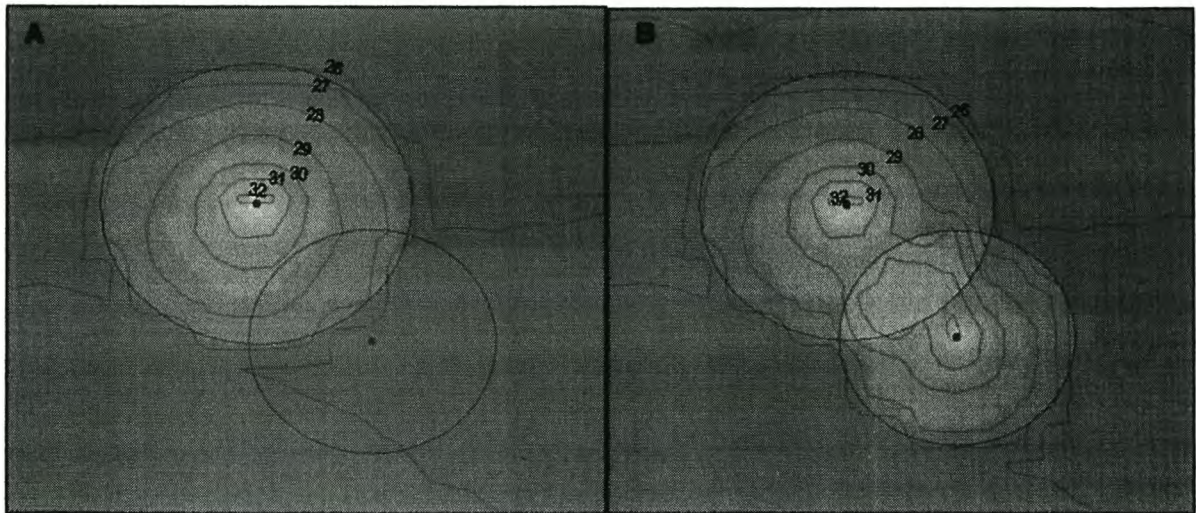

Figure 3.9: Drawdown as calculated for (a) a single abstracting borehole and (b) boreholes with overlapping drawdown zones.

CHAPTER 4: DEMONSTRATION

In this chapter GALET is demonstrated. The software was tested on datasets that comply with the requirements mentioned in Chapter 3. This chapter will show various screen shots of input boxes, reports and maps generated by the application.

As discussed in section 1.7, the Sandveld is an arid area in which groundwater abstraction has increased drastically in recent years. Fortunately, there is good groundwater related data available for this area, which makes it ideal for testing the system.

The following example will follow the same organisational procedures that have been set forth by DWAF to evaluate a new borehole request. These procedures were discussed with DWAF staff during the requirements study. The staff were also asked how they would want to integrate these procedures in the application. The following sections will give a step-wise layout of how the evaluation process takes place and how the various tools of GALET are used.

4.1 CHECK DATA SETS

For the system to function accurately, the data sets (as mentioned in section 3.1) must be set up correctly. The Department of Water Affairs and Forestry (DWAF) and Geohydrological and Spatial Solutions (GEOSS) provided the data sets for the Sandveld. It is important to have the most recent data sets available for water levels of the area. Seasonal data sets for water levels can also be used to indicate wet and dry seasons.

4.2 ADDING A BOREHOLE

When a new borehole has to be evaluated, the location, depth, abstraction rates (or volumes) and abstraction periods for the borehole needs to be specified. An input dialog box, as in Figure 4.1, is available to capture this information and is accessed from a dropdown menu called Borehole Tools. The input screen is based on the licence application forms provided by DWAF.

Each borehole must have a unique identifier, which can be specified in the "Borehole ID" input box. The user can check for duplicate borehole identification by clicking on the ID's

button next to the borehole identification entry box, which will open a list box containing borehole names. The borehole depth must be specified in metres.

The current water use application forms require that the exact location of the groundwater abstraction point be specified (see Appendix A, page 1). The user must specify the position of the borehole by entering geographic coordinates. The input screen accommodates Degrees/Minutes/Seconds (DMS) and Decimal Degrees (DD) coordinates. The correct datum of the coordinates must be selected with the Input Datum option – the user can choose between Hartebeesthoek 1994, referred to by DWAF as WGS84, or Cape.

Figure 4.1: Input screen for a new borehole.

The tool allows the user to input two abstraction rates: one for the wet or rainy period of the year and the other for the dry period of the year. The lengths (in days) of each of these periods can be specified. The abstraction amount can be entered as litres per second, volume per day or volume per annum. For this example, the summer (or dry period) rate was specified as five litres per second for 183 days and the winter (or wet period) rate as ten litres per second for 182 days. The total volume of abstraction was calculated as 236 304 cubic metres for a period of 365 days.

The new borehole is added to the borehole dataset by clicking the Insert Borehole Point button on the dialog box. In this example, the zone of influence, which is immediately calculated, has a radius of 300 metres for the first period and a radius of 460 metres for the full period (see Figure 4.2). The drawdown is not automatically calculated for the new borehole. This process is described in the next section. Standard Query Language (SQL)

queries can be constructed in ArcView to retrieve relevant information from external databases, such as DWAF's Water Management System (WMS).

The Abstraction Information tool ▣ in the toolbar can be used if a user wants to modify abstraction information such as rate of abstraction or abstraction period. A dialog box as in Figure 4.3 opens when a borehole is selected. The dialog box provides options for one or two abstraction rates and periods. The date at which abstraction starts can be specified and the end date is automatically calculated. A slide bar allows the user to easily modify the length of the periods of abstraction.
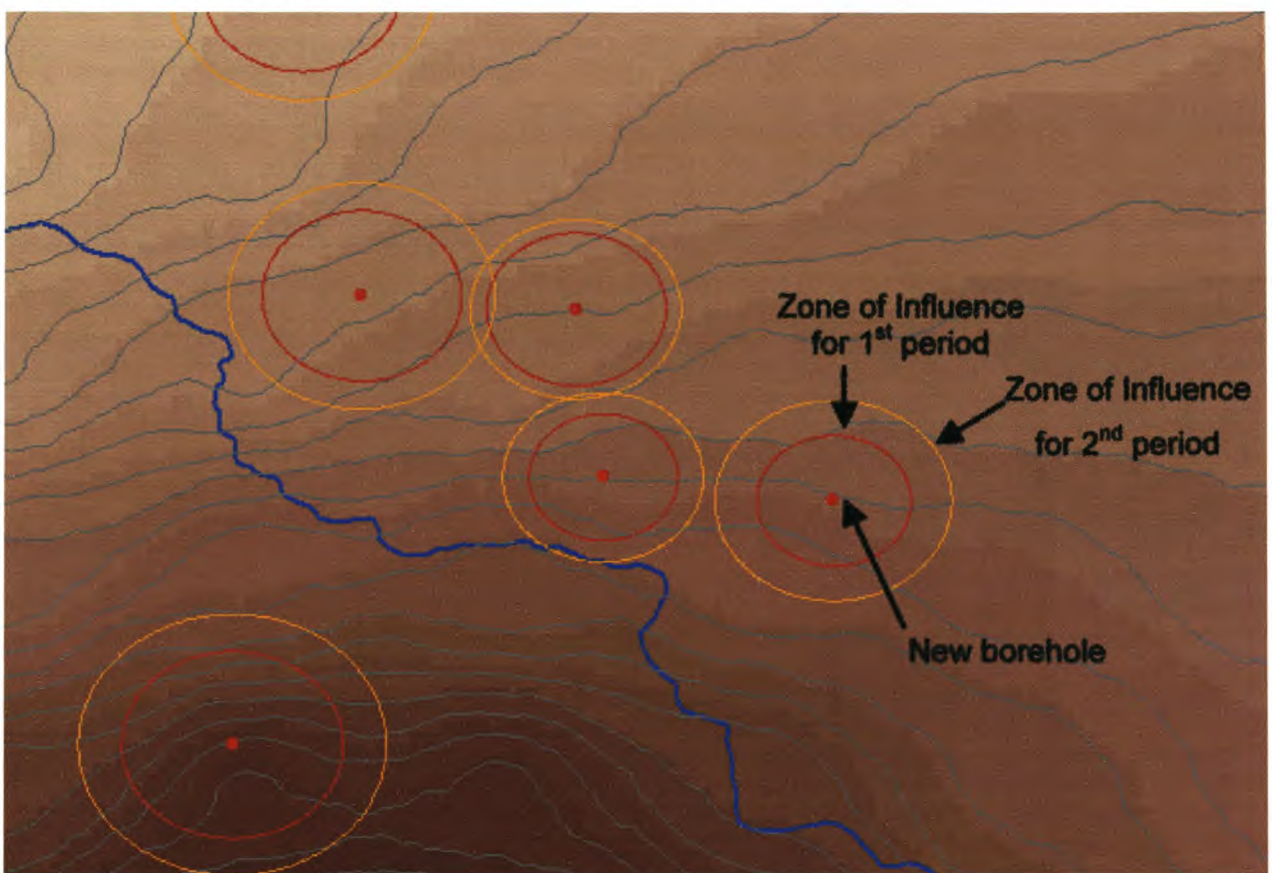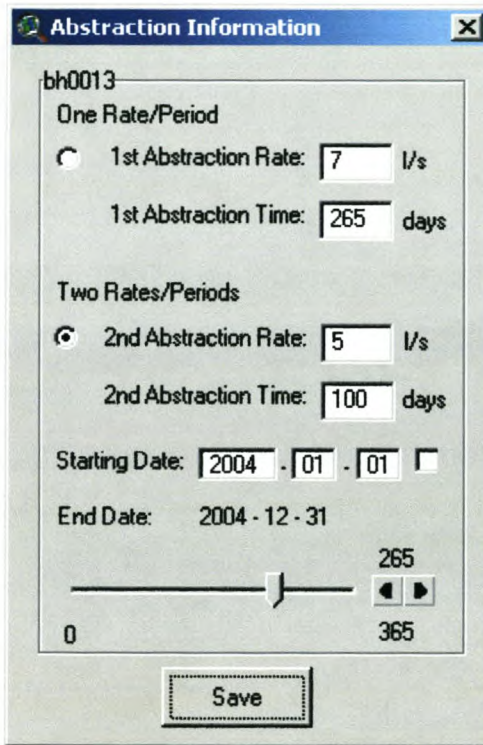

Figure 4.2: A new borehole that has been added to the borehole dataset.

4.3 CALCULATE DRAWDOWN

To start the process of calculating the drawdown for a selected borehole, a user can select the Add Drawdown tool ▣ in the toolbar. The Geological Information dialog box (see Figure 4.4) will open when the tool is selected. The user must then select the newly added borehole with the tool. The geological information for the selected borehole is displayed in the dialog box. Values for transmissivity (T) and storativity (S) can be retrieved from the data set containing lithological information by selecting the Original Data option. If the user has a
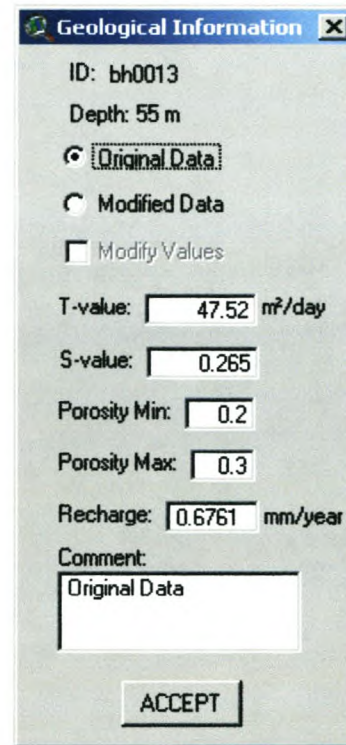
better knowledge of the aquifer characteristics, revised values can be used by selecting the Modified Data option. The Original Data option was chosen for this example and the results of calculating the drawdown can be seen in Figure 4.5. The contours for the water level, indicated by the grey lines, are declining towards the point of abstraction. The contours (in grey) are not symmetrical, which is a result of a sloping water table.

Figure 4.3: Dialog box to modify borehole abstraction information.

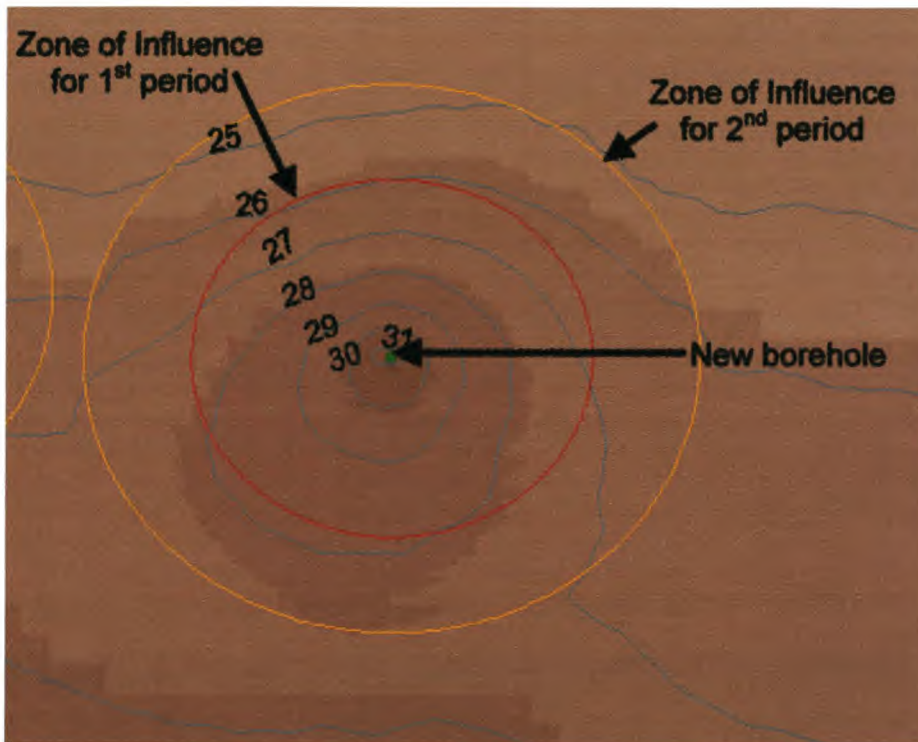Figure 4.4: Input dialog box for geological information.

Figure 4.5: Calculated drawdown for the selected borehole.

4.4 SET BUFFER ZONES

This is an additional and an optional step in the process of evaluating groundwater abstraction. The Buffer Zone tool can be used to assess whether the groundwater abstraction complies with resource quality objectives that have been set for the area. These objectives include safe distances to rivers and wetlands and a protected coastal zone.

The Buffer Zone tool ▼ can be selected from the toolbar to show the dialog box shown in Figure 4.6. This input screen allows the user to specify buffer zones, using metres as the units, around rivers, wetlands and other boreholes, and a safe distance from the coast. After the buffer zones have been specified, the user can select a borehole for the buffer zone analysis. In this example the buffer zones for the different features were set to 250m for rivers and wetlands, 750m for the coast and 100m for boreholes.

If the zone of influence does not overlap any buffer zones, the distance analysis results box (see Figure 4.7) will state that no buffer zones are reached. If the zone of influence overlaps the buffer zone of any feature, the results box will indicate (in the first line) what type of feature is affected as well as the period of abstraction that is allowed before the buffer zone is reached. This is followed by borehole depth and porosity information. The results box then gives abstraction information for the different abstraction periods. The result for the test case

was that the borehole's zone of influence does not overlap any buffer zone during the period of abstraction. The nearest buffer zone was that of a river at a distance of 498 metres from the borehole.

For the example in Figure 4.6, a borehole with two abstraction periods and two rates of abstraction over one year was selected. The first period is 100 days and has a rate of abstraction of ten litres per second. The second period is 265 days and has a rate of abstraction of five litres per second. For this example the results indicate that the closest buffer zone is that of a river at a distance of 55.3 metres from the borehole. The river's buffer zone was set at 170 metres. The borehole's zone of influence (ZOI) will not overlap the river's buffer zone during the first period of abstraction of 100 days. The ZOI will however reach the river's buffer zone 78 days into the second period of abstraction. This result indicates that the requested abstraction rates are too high or the period of abstraction is too long.
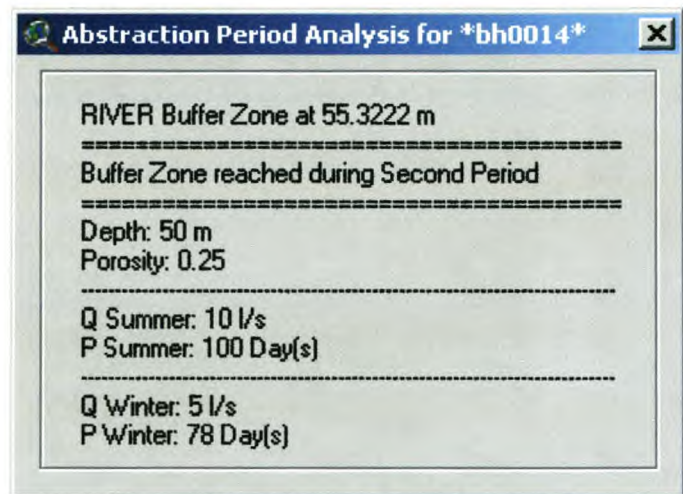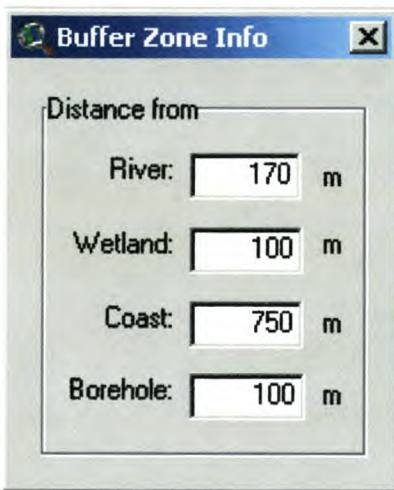
Figure 4.6: Dialog box for buffer zone information.

Figure 4.7: Results box for distance analysis.

4.5 GENERATE REPORT

GALET also provides a reporting function, which creates detailed maps in layout documents. The report is generated to summarise the evaluation of the groundwater abstraction from the selected borehole. The reporting tool of GALET uses the general authorisations to evaluate a borehole and determine whether the abstraction must be licensed or not. The general authorisations given by DWAF (see Table 4.1) indicate the annual volume of abstraction that is allowed per hectare. All catchments in South Africa have been classified according to DWAF's general authorisations (DWAF 2002).

Table 4.1: DWAF general authorisations.

General Authorisation Zone	Volume per hectare per annum (m^3)
A	0
B	45
C	75
D	150
E	400

Source: DWAF 2002

The report page showing water levels is similar to the report map in Figure 4.8. The report page that shows the general authorisations information is also similar to the report page in Figure 4.9.
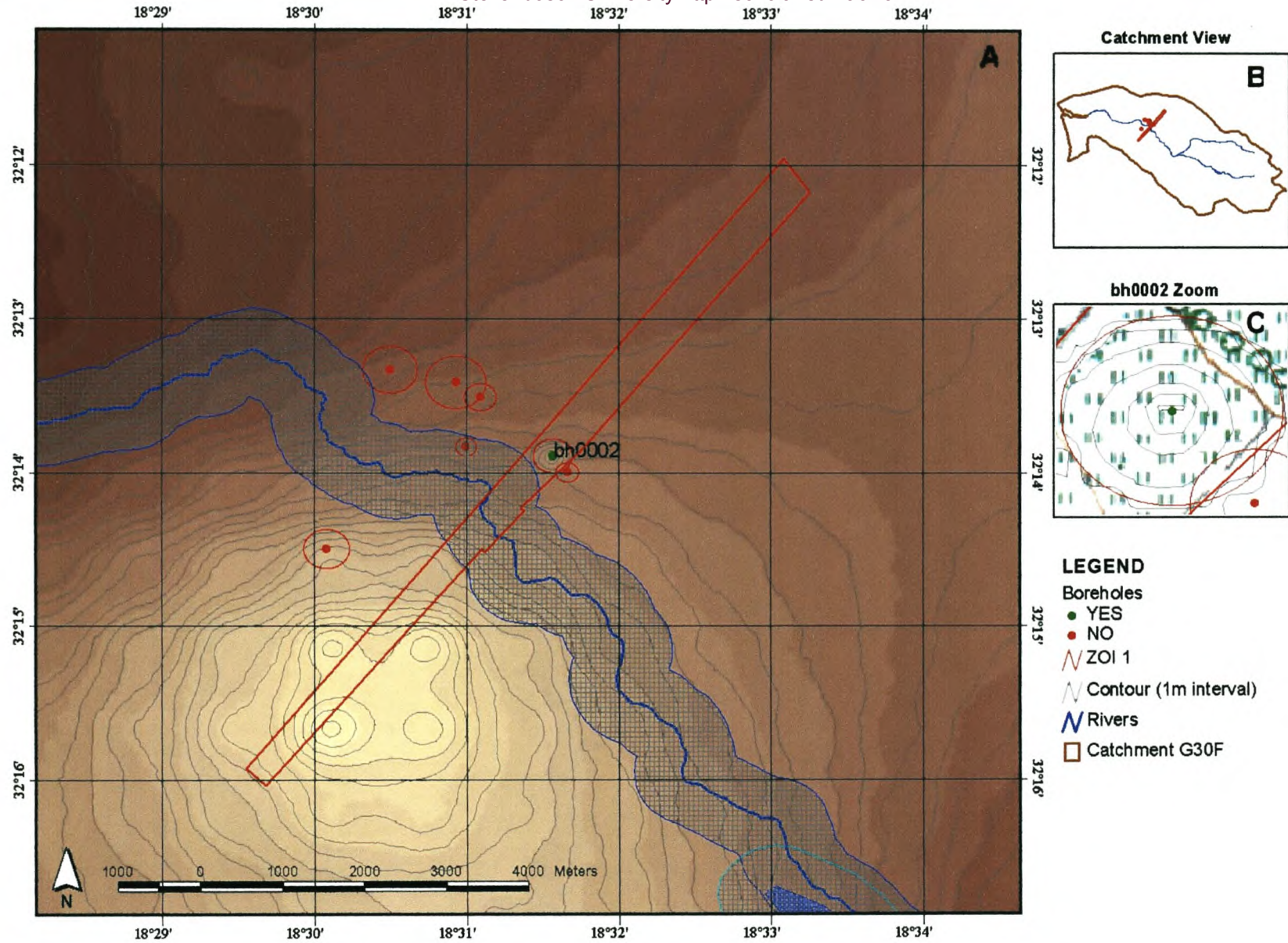
Figure 4.8: Report map displaying water level information.

Catchment: G30F

G.A. Zone: A

Limit: 0 m³/year OR 0 m³/ha/year

Borehole ID: bh0002

Farm Name: farm unknown

Farm Size: 358.98 Ha

SG Key: C02000000000022500070

Requested Abstraction Rates/Volumes

Wet Period: 8 l/s

Dry Period: 0 l/s

Total: 252288 m³/year OR 702.792 m³/ha/year

User Type

Licence	X
General Authorisation	
Schedule One	

Distance Analysis

River: 748.163 m

Wetland: 5674.45 m

Coast: 13701.5 m

Borehole: 251.013 m

Figure 4.9: Report containing general authorisations information.
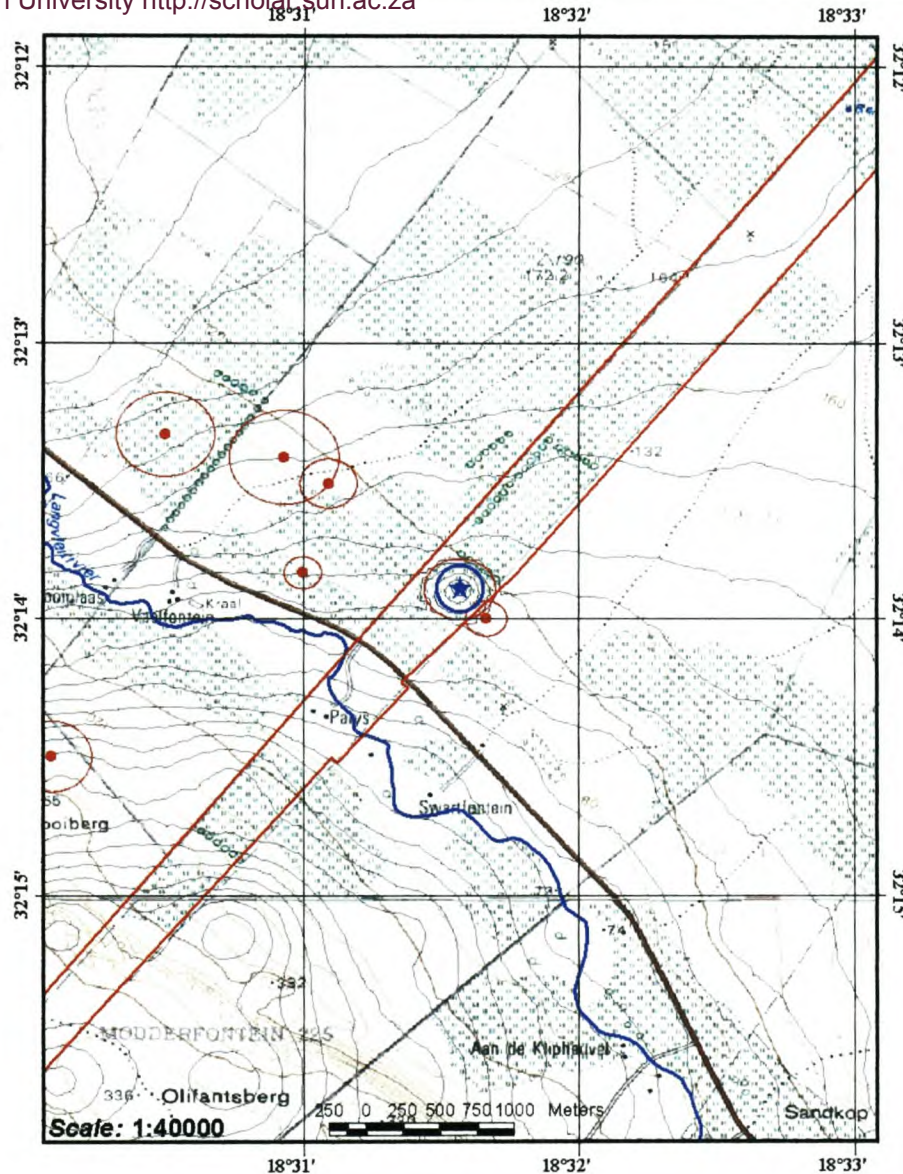
42

```
Catchment:     G30F
G.A. Zone:     A
Limit:         0 m³/year  OR  0 m³/ha/year

Borehole ID:   bh0002
Farm Name:     farm unknown
Farm Size:     358.98 Ha
SG Key:        C02000000000022500070

Requested Abstraction Rates/Volumes
Wet Period:    5 l/s
Dry Period:    10 l/s
Total:         236304 m³/year  OR  658.265 m³/ha/year

User Type
  Licence                          X
  General Authorisation
  Schedule One

Distance from Borehole to Feature:
River:         748.163 m
Wetland:       5674.45 m
Coast:         13701.5 m
Borehole:      902.384 m
```

Figure 4.10: General authorisations information as generated in the report for the selected borehole.

The main frame (A) in the report map of Figure 4.8 focuses on the cadastral boundary within which the borehole is situated. The map also shows other boreholes and their zones of influence, the water level grid, water level contours, rivers, wetlands and buffers zones. The coordinate grid is automatically generated for each new report map. Frame B in the top right corner of the layout shows the whole catchment and where the borehole is positioned in the catchment. The frame below it (C) is an enlargement of the area covered by the borehole's zone of influence. The backdrop for this frame is a 1:50000 topocadastral map to provide orientation.

The other report generated by the reporting tool contains DWAF general authorisation information for the area (see Figure 4.9). The general authorisation information for a selected borehole is displayed in the text on the layout report of Figure 4.10. This information includes catchment size, property size, requested abstraction rates and volumes, general authorisation evaluation and distance analysis details. The report also shows a map of the selected borehole and other boreholes in the vicinity on a 1:50000 topocadastral backdrop. Groundwater level contours are indicated by grey lines and a coordinate grid is automatically generated.

The results from the report pages should give an adequate indication of the impact that the requested groundwater abstraction will have. From these results a user would be able to make an instant decision that would allow or disallow the request for groundwater abstraction to proceed.

4.6 DELETING A BOREHOLE

A borehole is said to have run dry when the groundwater has been abstracted to a level below that of the pump in the borehole. This means that the borehole is no longer making an impact on the water level and can now be removed from the borehole data set. A borehole can also be removed from the dataset if it has been closed to terminate groundwater abstraction from the borehole. To remove a borehole from the borehole data set the user must select the Delete Borehole option from the Borehole Tools menu. This will open a dialog box, as in Figure 4.11, containing a list of all the current boreholes in the data set. Selecting a borehole identifier and clicking on OK removes the borehole.
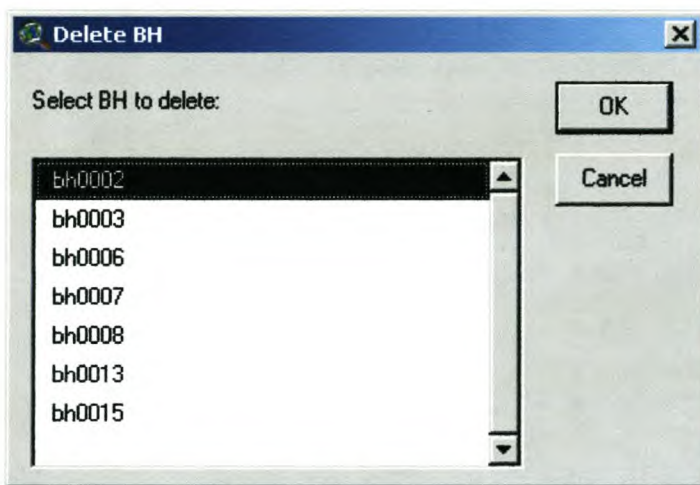
Figure 4.11: Selection box for removing a borehole.

When correctly applied, the tools demonstrated in this chapter can be used to perform a desktop evaluation of the groundwater abstraction. The tools allow for a fair degree of data manipulation and modification, especially when expert knowledge is available. The next chapter will discuss the current value and usability of the system, and also look at future developments and recommendations for improvement.

CHAPTER 5: RECOMMENDATIONS AND CONCLUSIONS

5.1 SUMMARY

With the occurrence of more frequent and longer droughts in South Africa (Scott, Fairbanks & Le Maitre 1998), water resources are under stress and water resource management is becoming more complex. Groundwater resources in particular are being impacted due to over-usage in certain areas. The Department of Water Affairs and Forestry (DWAF), the authority in control of water resource management, requires methods and tools that can assist in decisions regarding the sustainable utilisation of water resources.

The objective of this research was to create an SDSS that could serve as a tool for groundwater resource management, assist in the process of allocating water use licences and in determining the local impact of abstraction. GALET was developed in ESRI's ArcView 3.2 using the scripting language, Avenue.

The development of the application required a comprehensive study of groundwater theory and terminology. Many methods for groundwater drawdown calculation were evaluated. A technique that was common in various groundwater management software packages was selected and modified to deal with sloping water tables. The modified technique was extensively tested and the results were found to be adequate for the scale on which the tool is intended to be used. Existing methods for zone of influence (ZOI) calculations were also evaluated, but were found to be inflexible. Instead, a new method was developed that would provide the user with more accurate and realistic results.

Various data sets were collected for testing purposes. Groundwater related data for the Sandveld area were obtained from DWAF and Geohydrological and Spatial Solutions (GEOSS). This data included information on geology, rainfall, recharge and existing boreholes. Some data sets had to be modified and processed in order to be usable in GALET. The collected and processed data provided sufficient information to make an appropriate evaluation of the abstraction request.

A prototype with a simple graphical user interface (GUI) was created and discussed with DWAF staff members involved in critical decision-making pertaining to groundwater resources and groundwater licensing (in the Sandveld region and at national level). The

prototype was then further modified and presented to DWAF at different stages of the development process to ensure that GALET the system evolved gradually to comply with organisational requirements. The prototype was tested against collected data. Initial results showed the need for further modifications. The application was calibrated with the help of experts in the field of groundwater and then showed better results. The potential users approved the new results as well as the usability of the tool.

5.2 SUGGESTIONS AND MODIFICATIONS

Some suggestions were made about the implementation of the system and how to integrate it in the current licensing process. One of the suggestions was that it should be installed at DWAF regional offices, e.g. Bellville in the Western Cape, since all groundwater abstraction requests are processed at the regional offices for the respective provinces. It could then be used for instant assessments of the groundwater abstraction requests. A second suggestion was that should be installed on a web-server. This would allow users (registered at the web-server) to evaluate new abstraction requests without having to manage all the data sets involved. This would, however entail a redevelopment of the current system. A third suggestion was the integration of the system modules and tools into DWAF's groundwater management system, Regional Geohydrological Information System (REGIS). Since REGIS is an ArcView-based program integration would be relatively easy.

Like many other groundwater-modelling packages, GALET was developed for a specific purpose and does not cover all aspects of groundwater modelling. There are, however, further features that could be added to enable the user to perform additional impact assessments. New features would include a Reserve evaluation package, with which the user could determine the impact of abstraction at catchment, provincial or national level. Another feature that could be added is a flow-modelling package. This would allow the user to verify any groundwater pollution and assess groundwater quality for the future.

GALET, in its current state, requires data sets to be in a specific format. By improving the data set management system, the user would be able to use data sets that have not been processed beforehand. This data processing function would further enhance the system.

The system can be an effective tool in the process of allocating water use licences, in compliance with the National Water Act of 1998, and can play an important role in

determining the local impact of abstraction, which has become critical in the current climatic situation. Groundwater resource management in South Africa can benefit from the use of GALET to enable DWAF to work towards the goal of sustainable use of water for the benefit of all users.

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APPENDIX A: DWAF Water Use Registration Form

L2a   DW773

DEPARTMENT OF WATER AFFAIRS AND FORESTRY

LICENSING PART 2A	TAKING WATER FROM A WATER RESOURCE

Mark with X whether this is a new use ☐ *or* an amendment to an existing use ☐ (use number ☐☐☐☐)

1. WATER RESOURCE INFORMATION

1.1 Name of water resource

1.2 Name or reference number of abstraction point (if any)

1.3 Type of water source (mark only one with *X*)

☐ River or stream   ☐ Spring or eye   ☐ Borehole   ☐ Dam   ☐ Estuary

☐ Wetland   ☐ Lake   ☐ Canal

☐ Other   (Description of other)

1.4 Geographic location of the abstraction point

S ☐ ° ☐ ' ☐☐.☐ " or S ☐☐.☐☐ ° or S ☐☐ ° ☐☐.☐ '   Cape datum Clarke 1880 ☐

E 0 ☐ ° ☐ ' ☐☐.☐ " E 0 ☐.☐☐☐ ° E 0 ☐☐ ° ☐☐.☐ '   WGS-84 datum HBH94 ☐

1.5 Reliability of water resource (mark only one with *X*)

Water always available ☐   Dry during certain seasons ☐   Frequently dry ☐

2. DESCRIPTION OF WATER USE

2.1 The water is used for (mark all uses with *X*):

Agriculture: irrigation   ☐ (also complete form DW787)

Agriculture: watering livestock   ☐

Aquaculture   ☐

mining   ☐ (also complete form DW788)

Industry, commerce, power*   ☐ (also complete form DW788)

Domestic or urban water supply*   ☐ (Local authorities also complete form DW789)

Recreation   ☐

Other (specify)   ☐

2.2 Amount of water taken

a) Date of first use or proposed first use   Y Y Y Y M M D D

b) The total amount of water abstracted per year is   ☐☐☐☐☐☐☐☐ cubic metres

c) Transmission losses amount to   ☐ %

L2a   DW773

2.3 Seasonal patterns of water usage

a)   the estimated water abstraction pattern is: (In total cubic meters ☐ Or % per month ☐):

Jan	☐☐☐☐☐☐	Apr	☐☐☐☐☐☐	Jul	☐☐☐☐☐☐	Oct	☐☐☐☐☐☐
Feb	☐☐☐☐☐☐	May	☐☐☐☐☐☐	Aug	☐☐☐☐☐☐	Nov	☐☐☐☐☐☐
Mar	☐☐☐☐☐☐	Jun	☐☐☐☐☐☐	Sep	☐☐☐☐☐☐	Dec	☐☐☐☐☐☐

b)   ...or roughly (mark only one with X):

☐ all year round   ☐ mainly in the wet season   ☐ mainly in the dry season   ☐ not sure

---

2.4 Method of abstraction

a)   mark with X the abstraction methods currently being used or that are to be installed or constructed:

☐ pump   (also complete form DW784: *Pump Technical Data*)

☐ canal   (also complete form DW785: *Gravity or Outlet Pipe Technical Data*)

☐ gravity or outlet pipe   (also complete form DW786: *Canal Technical Data*)

☐ other (specify):

---

3. EXISTING AUTHORISATION AND REGISTRATION

3.1	Water use started on		Y Y Y Y M M D D

3.2   If this is an existing water use, mark with X and enter permit numbers ☐

permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D
permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D
permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D
permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D
permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D
permit number	☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐☐	date	Y Y Y Y M M D D

3.3   If water use takes place in terms of the General Authorisation, mark with X: ☐

Law / Regulation

3.4   If an authorisation was issued under other legislation:

L2a   DW773

4. LIST OF ATTACHED FORMS AND DOCUMENTS

4.1 Supplementary forms attached with this form   number

   a) DW787: Irrigated Field and Crop Information

   b) DW788: Power Generation, Industrial or Mining Use

   c) DW789: Domestic, Urban, Commercial or Industrial Use

   d) DW784: Pump Technical Data

   e) DW785: Gravity or Outlet Pipe Technical Data

   f) DW786: Canal Technical Data

4.2 Specify the number of other documents submitted with this form   number

   a) Environmental impact assessment

      Other: (specify) D W

      Other: (specify) D W

      Other: (specify) D W

      Other: (specify) D W

FOR OFFICIAL USE ONLY

File number

Water use register number

Received by:

surname   initials

rank

signature

Captured by:

initials

Date stamp of receiving office

APPENDIX B: Script call procedures

Tool Function: Calculate drawdown

Scripts used	Description	Scripts called
calcrech	Calculatesthe recharge at a given point	
dd_add_tool_go	Calculates the ZOI and drawdown for the selected borehole and adds the new water level grid to the view showing the drawdown influence of all the boreholes in the catchment	contour_make dd_clear dd_calc_plus grid_makeDDgrd sector_run zoi_time
dd_atradius	Calculates the drawdown at 10 metre intervals from the borehole	
dd_calc_plus	Calculates the drawdown with a flat water table at 10 metre intervals from the borehole to the ZOI with the specified abstraction rates and abstraction periods for the selected borehole. Results are captured in the vector theme called Drawdown. (*section 3.4, step 1*)	dd_atradius
dd_clear	Clears the temporary drawdown theme	
getgeology	Retrieves the geological information from the different data sets for a given point	calcrech
grid_makeDDgrd	Makes a drawdown grid from the Drawdown theme created by dd_calc_plus (*section 3.4, step 2*)	
sector_run	Runs the procedures to create a drawdown grid with a sloping water table for the selected borehole (*section 3.4, steps 1-7*)	sector_make sector_grdrelslope sector_grdcombine sector_grdnewang sector_drawdown
sector_make	Creates a selection zone which will be used to select a portion of the ASPECT grid (*section 3.4, step 3*)	
sector_grdrelslope	Creates a grid of relative direction (*section 3.4, step 4*)	
sector_grdcombine	Combines the ASPECT and SLOPE grids (*section 3.4, step 5*)	
sector_grdnewang	Calculates the angle of the water table according to the relative slope direction (*section 3.4, step 5*)	

| sector_drawdown	Calculates a new drawdown grid for a sloping water table (*section 3.4, step 6*)	
zoi_time	Calculates the ZOI for each borehole with their specified abstraction rates and abstraction periods	dd_atradius getgeology zoi_check zoi_clear zoi_draw
zoi_check	Loads the ZOI theme and sets the predefined legend for the theme	
zoi_clear	Resets the ZOI theme	
zoi_draw	Draws the new ZOI circles in the view	
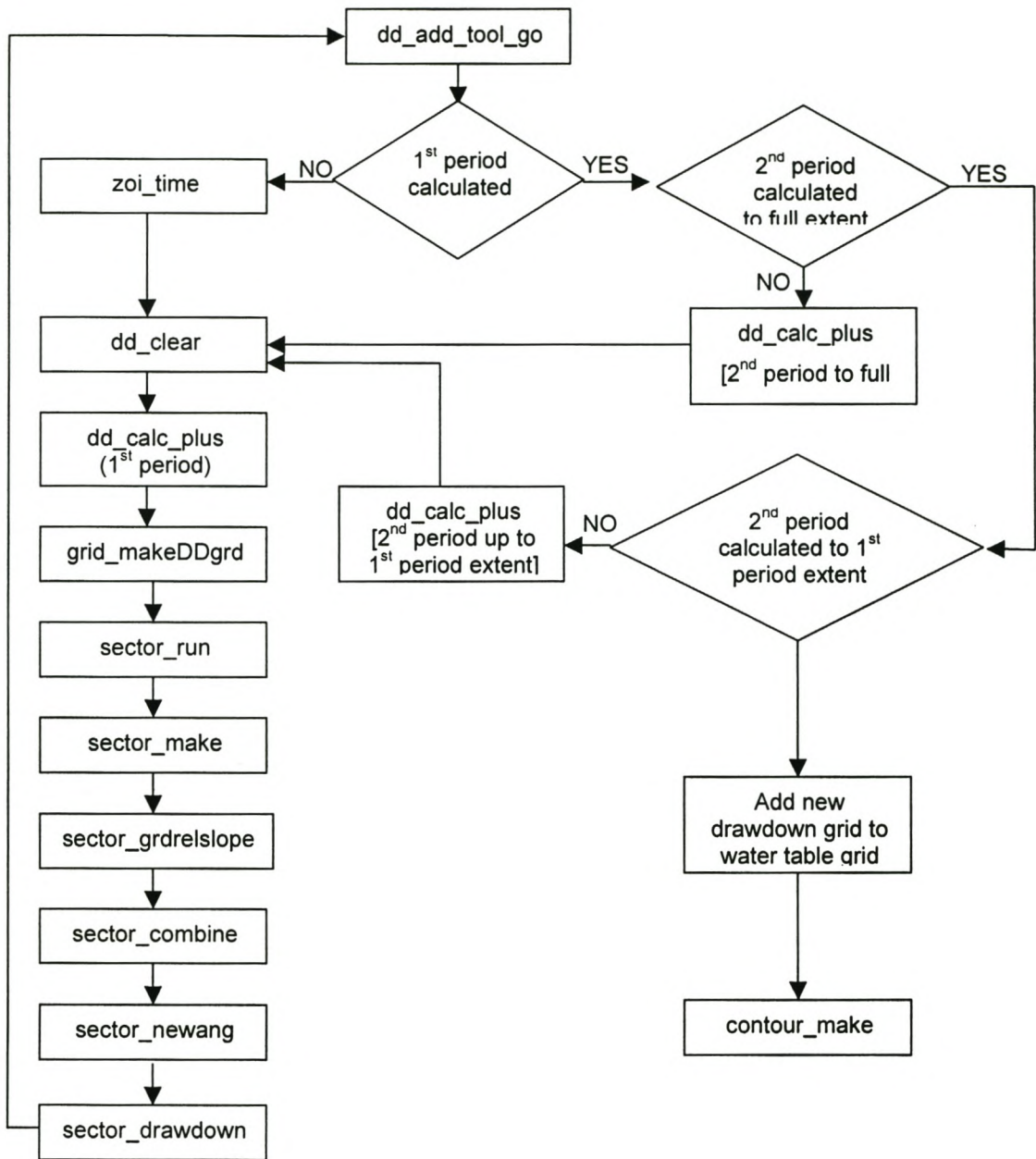
Figure B.1: Flowdiagram for scripts used in the drawdown calculation process.