HYDROGEOLOGICAL AND ISOTOPIC ASSESSMENT OF THE RESPONSE OF A FRACTURED MULTI-LAYERED AQUIFER TO LONG TERM ABSTRACTION IN A SEMI-ARID ENVIRONMENT

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Water Research Commission

HYDROGEOLOGICAL AND ISOTOPIC ASSESSMENT OF THE RESPONSE OF A FRACTURED MULTI-LAYERED AQUIFER TO LONG TERM ABSTRACTION IN A SEMI-ARID ENVIRONMENT

Report to the
WATER RESEARCH COMMISSION

by

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EXECUTIVE SUMMARY

The assessment of recharge to fractured Karoo aquifers, especially below a substantial cover of Kalahari deposits, has occupied the minds of many researchers. This project follows several approaches to the problem: isotope data obtained from pumping tests are used to assess ground water mean residence times, from which integrated recharge rates can be deduced. The method of cumulative rainfall departures is applied to long-term rest level, pump rate and rainfall observations.

The study originated as an attempt to use long-term, well-documented abstraction of ground water at the Orapa mine, Botswana to evaluate critically borehole pumping tests of fractured Karoo aquifers, which are of necessity limited in their duration. As a more comprehensive investigation was being carried out by Anglo American, the present study was redirected, focussing specifically on the refinement of recharge estimation in the area. An original objective, the characterisation of the Karoo aquifers in the Orapa/Lethlakane area as compared to similar aquifers in South Africa using a new method of interpreting pumping tests, was retained in the revised project.

The aims of the present Water Research Commission Project, having been redefined were:

1) Assessing the recharge to the aquifer using different methods. Appropriate techniques to be considered were:
   - an integrated water balance method,
   - chloride profiles,
   - the cumulative rainfall departure (CRD) method,
   - tritium profiles from previous studies,
   - recharge assessment based on the radiocarbon concentration of the ground water.
2) To reach a better understanding of the effective mechanism of recharge and to assess the reliability and value of isotopic measurements in ground water studies, especially in Karoo aquifers, in a semi-arid environment.
3) To characterise the aquifer in terms of its hydraulic response by re-examining data on pumping tests conducted previously.
4) To collate the findings of the investigation in a report.

Ground water at Orapa mines has been investigated by different consultants since the latter sixties. In the early seventies, recharge to aquifers in the Kalahari was regarded as negligible. This was challenged by environmental isotope studies, initially conducted at Orapa and subsequently extended to the Kalahari in general.

The area, of featureless topography, lies in the central Kalahari, with average annual rainfall 350 mm.

The main stratigraphical units of the geology are: the archaean metamorphic and granitic basement rocks; the Karoo sequence consisting of the upper Ecca, Mosolotsane and Ntane sandstone formations; Stormberg lavas and a cover of Kalahari Beds. There are intrusions of Kimberlite and extensive dolerite dykes.

Tectonic activity produced a system of larger and smaller intersecting fractures, only some of which are intruded by dykes, and horst and graben structures, all of which play an important role in the occurrence of exploitable ground water.

The Kalahari Beds hold ground water which sustains shallow boreholes and hand-dug wells. The Stormberg basalt acts as a confining layer over the underlying Ntane and Mosolotsane, has fracture zones, but is not regarded as suitable for exploitation. The Ntane sandstone is the main aquifer of the area, with relatively high intrinsic porosity and secondary permeability, sustaining yields from deep boreholes of up to 110 m^3/hr. The Mosolotsane is a poor aquifer, containing poor quality water. The dykes act partially as barriers to ground water flow, and partially as permeable zones.

Exploitation from the five well fields established at the mines rose from 225 megalitres per month in 1984 to 528 megalitres per month in 1992.

The earliest indications that recharge was occurring came from isotope observations. Water balance studies confirmed these conclusions, and showed that recharge can be quantified in spite of it being small. These conclusions have a significant impact on the water household at the mines.

Various methods for assessing recharge in this environment are reviewed. In the unsaturated zone, chloride and environmental tritium profiles can be employed in moisture in cores of sand or soil. The chloride method relies on the increase in concentration of chloride in soil moisture due to evapotranspiration. Tritium profiles trace the increase of tritium in rain following the thermonuclear test period of the early sixties. Although these methods can be used to assess the downward movement of moisture in the soil matrix, the spatial and temporal variability of soil moisture conditions and the existence of preferential or bypass flow, complicate the interpretation of such profiles in terms of ground water recharge. Typical recharge values calculated lie in the range of a few mm of water column per annum.

Sporadic recharge events would constitute a regionally averaged long-term diffusive recharge. Environmental radiocarbon labels rainwater entering the saturated zone. Its concentration as measured in water pumped from a borehole can be interpreted in terms of a ground water mean residence time. If the depth of water column being exploited and the porosity of the aquifer can be ascertained, a recharge rate can be calculated. The assumption when assessing the mean residence time is that ground water flow lines develop, obeying the so-called exponential model. Although ground water in the area is not subject to significant regional flow, it is shown that successive layering due to recharge produces a degree of "age" stratification.

The resulting age stratification is assumed to be approximated by the exponential model, as the boreholes would tap and mix the stratified zone. As radiocarbon with a mean life of 8270 years will be able to label all the water in the aquifer through diffusion, the total porosity rather than the storativity, which is orders of magnitude smaller for a confined aquifer, is appropriate in this regard. Although isotope data was obtained for Orapa since 1969, only the data gathered since 1987 is considered. With only one exception, first strike water obtained at the basalt/sandstone interface is found to have low radiocarbon values, indicating residence times of many thousands of years. This is taken to indicate that (lateral) flow in the Ntane is very slow. This, and the absence of any visible discharge from the ground water system, indicates that only evapotranspirative losses are important. As good porosity values are available for the Ntane, mean recharge values based on radiocarbon-derived mean residence times were calculated, which lie in the range of 1 - 3.7 mm a^{-1}. The higher value was obtained including data on a borehole which happened to be drilled in a section of the basalt with high vertical permeability. Very consistent stable isotope values, independent of residence times, show no great variability in climate over the time span indicated by radiocarbon measurements of the ground water.

Three water balance techniques are discussed in terms of the long-term exploitation of the aquifers. i) Saturated volume fluctuation using a finite-element grid over the entire aquifer, but applied only to well fields 4, 5 and 6. Average storativities of some 0.00075 and recharge of some 1.4 % of mean annual rainfall were obtained. ii) Recharge derived from periods of equal volume showed for the first time a 4 month lag of water level response to an anomalous rainfall event in wellfield 6. An apparent lateral recharge component may result from insufficient coverage of the area with observation boreholes. The adapted Hill method assumes a linear relationship between abstraction and change in saturated volume.

The cumulative rainfall departure (CRD) method calculates the departure of rainfall in individual months from the long-term mean. Only positive values are considered. Recharge is then taken to be proportional to these departures, with a constant of proportionality depending on the short-term response of the system. A linear correspondence is also assumed between water level response and the CRD series. The uncertain storativity of the aquifer precludes the calculation of recharge using this method. The modified CRD relationship relates the average rainfall over a few months to the average over several years - so-called short-term and long-term memory - which reflect changes in rainfall and variable loss mechanisms respectively.

Various correlations are attempted. For n (long-term memory) of 36 months, the best correspondence is obtained and the correlation increases for m (short-term memory) from 1 to 12 months.

For n = 60 the correspondence is poorer and declines for m increasing from 1 to 12 months.

Correlations decrease to n = 120 months; decrease for m = 1 to 3 months but improve slightly for m up to 12 months.

It is concluded that ground water levels conform more closely to average rainfall over 12 months than averages over shorter intervals. This is taken to reflect the integrating effect of the soil overburden. For the CRD relationship with $m<n$, the losses from the system are most closely related to the average rainfall over the preceding 36 months.

The effect of abstraction is accounted for by including this factor in the constant of proportionality, linking CRD with recharge. For well field 6, the best fit regression is obtained for a value of the constant somewhat greater than one, assuming constant abstraction. Using this constant in the CRD series for Orapa/Lethlakane the rest level correlation coefficient improves from 0.86 to 0.92. Various factors, such as the nature of the aquifer and the presence of dykes will determine the area of influence. The correlation increases until the area is reduced to less than 1 km^2. This shows that pumping dominates the water level response.

The correlation is found to improve even further when the short and long-term memory of the system are reversed. The implication is that the effective recharge which controls the response of the ground water levels is lower when the average rainfall over the preceding months is higher than the long-term average. Although difficult to conceptualise in hydrological terms, this phenomenon can be understood in terms of enhanced vegetation activity in response to higher soil moisture which in turn inhibits recharge. Such a mechanism was proposed to explain isotopic values in ground water in Gordonia. Alternatively, the best fit between the normal cumulative rainfall departures and ground water levels is attained incorporating a lag of 14 months.

Further modifications to the recharge-CRD relationship take account of the equivalent ineffective rainfall, and pumpage, as well as the lag in response. These increase the correlation coefficient to 0.99 and produce a CRD series which best predicts the aquifer behaviour at Orapa. Its applicability to other areas needs to be investigated.

Aquifer storativity is assessed using integrated fluctuation of saturated volume. It has been established that values of the storativity decline with increasing distance of the observation borehole from the pumped borehole using normal interpretations of pumping tests. As experience had shown that all pumping tests at Orapa showed similar behaviour, a limited number was re-examined. The data was obtained from drawdown graphs, and analysed according to the methods of Theis, Walton and Moench. The results conform reasonably with those obtained for the Karoo formations in the Free State, and a storativity value of 0.0035 is inferred for Orapa.

The phenomenon of declining S values with increasing distance to the observation well elicited comment by Professor Neuman of Tucson, Arizona. He points out that in fractured aquifers world-wide there is a nesting of parameters. With a continuous local range of S and T values, the early log-log behaviour would resemble a Theis curve, and only longer pumping tests would reveal deviations. These remarks are in agreement with the analysis of the isotope data and the similarity in behaviour caused by the fractal feature of different southern African aquifers.

Revised interpretations of all suitable pumping tests would require a comparison of the storativity values obtained with those based on water balance, in order to arrive at realistic figures. This study has led to a better understanding of the behaviour of fractured aquifers.

The study has shown further that the quality of the pumping test data was not as good as initially assumed. Water balance methods gave consistent values of recharge, but not of storativity, the best value of which at 0.0035, gives a recharge rate of a few mm/a. Flooding of the ephemeral Lethlakane river could locally contribute significantly to this recharge.

Recharge rates based on radiocarbon observations in the saturated zone confirm the value obtained from water balance considerations. Both as qualitative indicators of aquifer behaviour and in quantitative interpretation of recharge, isotope methods have the advantage of not having to rely on long-term observations. In view of the largely confined aquifer conditions, values in the range of 1 - 3.7 mm/a from isotopes compare reasonably with values of 1.75 - 4.8 mm/a from CRD, using values of porosity and storativity of 0.2 and 0.0035 respectively.

The modified CRD method with reversed long term and short term responses, incorporating a pumping factor and a rainfall response lag of four months, simulates water level responses to both recharge and abstraction.

The objectives of the study were realised, in that reasonably consistent values of recharge were obtained from both water balance and radiocarbon methods which in turn agree in general terms with estimates by other workers based on chloride and tritium profiles in the unsaturated zone.

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HYDROLOGICAL ASSESSMENT OF THE RESPONSE OF A FRACTURED MULTI-LAYERED AQUIFER TO LONG-TERM ABSTRACTION

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The research covered in this report was guided by a Steering Committee consisting of the following persons:

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PREFACE

Since 1969 the Schonland Research Centre for Nuclear Sciences (formerly the Nuclear Physics Research Unit) of the University of the Witwatersrand has been involved in hydrological, isotopic and hydrochemical studies of the ground water in the Karoo aquifers at the Orapa diamond mine in Central Botswana (Mazor et al. 1974, 1977; Verhagen et al. 1974). From the latter 60's, several South African and international firms and individuals have been involved in geohydrological investigations in the area during both exploratory and exploitation phases of a reliable water supply for the mine and assessment of the exploitation potential.

The present study originated as an attempt to use the long-term, well-documented abstraction of ground water at Orapa to evaluate critically borehole pumping tests of fractured Karoo aquifers, as these are of necessity limited in their duration. As such, it had been accepted as a Water Research Commission project. However Anglo American Corporation (AAC) initiated their own investigation to develop a management strategy for the entire aquifer both for water supply and for the purpose of continued mining.

To avoid duplication of the more comprehensive investigation carried out by AAC, the present investigation was directed at a re-examination of the geohydrological information pertaining to the Orapa/Letlhakane region, focussing specifically on further refinement of recharge estimation in the area, and the determination of the storativity and other characteristics of a fractured aquifer. These were aspects which were not being covered in full by AAC. The present investigation was also to include a) the assessment of recharge through a quantitative evaluation of isotopic data which had been collected over several years, b) using the method of cumulative rainfall departures to determine recharge and c) to examine a simplified approach to model the response of the aquifer to recharge from rainfall and the effects of pumping on the system.

The original objective, i.e. the characterisation of the Karoo aquifers in the Orapa/Letlhakane area in comparison to similar aquifers in the Republic of South Africa, using a new method of interpreting pumping tests, was retained in the revised project.

1. INTRODUCTION

The water supply of the diamond mining operations at Orapa and Letlhakane is derived from ground water occurring in the Karoo formations of which the Ntane Sandstone (the equivalent of the Clarence Formation in the RSA) is the main aquifer. Various well fields have been established around the mines. Because of the low recharge, prolonged droughts and an ever-increasing demand for water, ground water levels have declined over a large area. In some instances the interference between boreholes was high, leading to diminishing yields from well fields.

The ability to exploit ground water at acceptable rates to supply the mines seems to be associated with fracturing by block-faulting, and regional dykes traversing the aquiferous formations. The faults have occurred due to structural upheaval and subsidence, resulting in a complex aquifer system.

The AAC is interested in ground water in the Orapa/Letlhakane area in order to:

1) provide an assured supply of water to the mine and to the mining community;
2) ensure that the rate of dewatering drawdown in the open-mine pits is sufficient to continue mining operations at their planned capacities.

The determination of recharge and storativity can be difficult, especially in a semi-arid environment. Recharge has been successfully estimated using isotopic and other methods in similar environments (Verhagen 1995, 1999), and such methods are reported for the Orapa/Lethlakane area (Section 4.2.2). The water balance methods which have been put forward by Bredenkamp et al. (1994) should be ideally suited to estimate these parameters, and are reported below. The reappraisal of available geohydrological information for the area has led to a better understanding, and allowed a more reliable assessment of the exploitation potential, of the system.

The Orapa/Letlhakane aquifers provide an excellent case of a fractured hard-rock aquifer in a semi-arid environment. If a reliable estimate of the recharge could result from the study it would supplement previous research projects sponsored by the Water Research Commission, by extending the application of the methods to different arid regions. The Orapa/Letlhakane study may also provide further confirmation of the regional rainfall/recharge relationship which appears to hold for most of the RSA.

Objectives

The *original* objectives of the study had been defined as follows:

1) to establish a data base of all available hydrogeological information conforming to GIS (Geographical Information System).

2) to establish the extent and the characteristics of the aquifers in the study area in comparison with the Karoo sequence in the RSA

3) to develop a preliminary mathematical model for assessing the response of a fractured and multi-layered aquifer to long-term abstraction with specific attention to the analysis and evaluation of test pumping results

4) to assess recharge to the fractured aquifer using isotopic data, hydrochemistry and

water-level monitoring data.

The objectives defined for the study which was conducted by AAC not only overlapped the original aims of the present project, but covered a larger area and several aspects, such as the geology and management of the aquifer, more extensively.

The *redefined* aims of the present Water Research Commission Project are:

1) Assessing the recharge to the aquifer using different methods. Appropriate techniques to be considered:
- an integrated water balance method,
- chloride profiles,
- the cumulative rainfall departure (CRD) method,
- tritium profiles from previous studies,
- recharge assessment based on the ^{14}C concentration of the ground water.

2) To reach a better understanding of the effective mechanism of recharge and to assess the reliability and value of isotopic measurements in ground water studies especially in Karoo aquifers in a semi-arid environment.

3) To characterise the aquifer in terms of its hydraulic response by re-examining data on pumping tests conducted previously.

4) To collate the findings of the investigation in a comprehensive report.

The object of the study was therefore not to carry out any field investigations or to collect additional data (although the collection of follow-up isotope data was mooted), but to analyse only available information. It was also not the intention to duplicate any of the work which had already been done by AAC. Some of their results on the recharge and storativity of the system are included for comparison in the present study.

Area of Investigation

The main area of investigation is shown in Fig. 1.1.

The establishment of a diamond mine in the late 1960's at Orapa and Letlhakane in the central Kalahari required an assured water supply. Since 1984 the Orapa mine has been supplied solely by ground water. Ground water has been investigated by different consultants over the years (e.g. Gibb 1969; Verhagen et al. 1974; Mazor et al. 1974,1977; Foster et al. 1982;

Steffen Robertson and Kirsten, 1980 - 1988), and different well fields have been established. Studies by Gieske (1992), in the vicinity of Gaborone, some 500 km to the south, and Verhagen (1995) have revealed a great deal about recharge in that area, albeit in somewhat different physiographic settings.

Initial estimates of the ground water potential in the Orapa/Letlhakane area were based largely on pumping tests and modelling with which the rate of decline in water-levels was predicted. In view of the need to extract the ground water intersected in the open-cast pit and ensuring a reliable supply of water to the community involved in the mining operations, ground water storage and siting of high yielding boreholes had received a higher priority than the estimation of recharge. In the early 70's, recharge to Kalahari aquifers was regarded as negligible (Martin, 1961). This proposition was challenged by environmental isotope studies conducted by Verhagen et al. (1974) and Mazor et al. (1974, 1977) on ground water in the wider area around Orapa mine, and the Kalahari in general (Verhagen et al. 1979; Verhagen 1984, 1990,.1993, 1995).

Both recharge and aquifer storativity are vital parameters in the effective management of ground water resources and in predicting the rate of decline of ground water levels. Ground water quality is not addressed in the present study.

The need for reliable siting of boreholes and identifying in advance the best areas for extending the well fields was clearly realised by the mining corporation and has led to extensive geophysical surveys and geological exploration to identify the main factors controlling the occurrence of ground water. The most recent geohydrological study of the area by AAC (Van Rensburg and Bush, 1995) was a major investigation during which all available information was collated. Much was revealed about the geology of the area in a report by Bush and Blecher (1993) based on a geological model and supplemented by geophysical information, LANDSAT images and geological logs obtained from exploration and water-supply boreholes.

Physiography and Climate

The area of investigation, depicted in Fig. 1.1, lies in the semi-arid to arid central Kalahari. Rainfall decreases from the north to the south and from the east to the west as can be seen from the isohyets of average annual rainfall. The average precipitation in the region of Orapa is about 350 mm/a and is only slightly higher in the Letlhakane region. The topography (Fig. 1.2) is generally featureless, which ensures a low diversity of climate. Rainfall in the Orapa/Letlhakane area is erratic and occurs as local and more regional thunder storms, predominantly in summer (October to April).

The potential evapotranspiration is high due to the high temperatures and low humidity. Evaporation from open water bodies is in the range of 2 metres per year. Based on the Penman equation the daily potential evapotranspiration for the Pitsanyane Basin, close to Lobatse, was estimated to vary between 8 mm for mid-summer and 3 mm for the winter months (Gieske, 1992).

Gieske (1992) deals extensively with the temporal distribution of rainfall in the area around Lobatse and Kanye, and has obtained rainfall samples for the determination of their chloride concentration to derive the recharge from chloride balances. Based on careful measurements of rainfall showers, the distribution and intensity of rainstorms showed a rather similar statistical pattern for events exceeding 1 mm. The average depth of precipitation per event is about 8,5 mm and the average duration 3,3 hours.

The maximum observed rainfall event in Gieske's study is about 50 mm with a maximum duration of 24 hours. The range of possible rainfall amounts, intensities and durations is however likely to be much greater than suggested by these observations. The time between events is large. The spatial correlation of daily rainfall decreases as the distance between stations increases, as could be expected. Reasonable correspondence in daily rainfall is still apparent over distances of 10 km (Gieske, 1992), but this does not necessarily apply to Letlhakane with its lower and more erratic rainfall.

Runoff

The importance of runoff is that it produces concentrated or focussed recharge of ground water by more direct infiltration into permeable colluvial and alluvial zones or fans - a function of the frequency, magnitude and duration of runoff. A large concentration of successful boreholes is situated along the ephemeral Letlhakane River which produce better than average quality of ground water.

Recharge may also be related to local depressions which can accumulate runoff from the surrounding area. It is however impossible to identify all of these depressions and the recharge which they effect. For this reason a more integrated approach places more reliance on the analysis of the water balance of the entire aquifer (see Section 5).

2. GEOLOGY

The geology of an area is important in the assessment of the ground water resource as it has a bearing on the rate of infiltration, the size of the underground storage and the rate at which ground water can be abstracted from the aquifer. In the case of hard-rock formations water is stored in the fractures within the rock as well as in the matrix. During abstraction water predominantly flows along the major fractures which in turn are fed by a hierarchy minor fractures and pores.

The four major stratigraphical units of the geology at Orapa/Lethlakane are:

1. Archaean metamorphic and granitic basement rocks, which underlie the Karoo succession and are not considered to be hydrogeologically important
2. An extensive Palaeozoic to Mesozoic succession of Karoo strata, consisting of the upper sequence of the Ecca Group which is unconformably overlain by the Mosolotsane and the Ntane Formations.
3. The basalts of the Stormberg Lava Group which overlie the Ntane sandstones.
4. A cover of late Cretaceous to Recent Kalahari Beds (see Fig. 2.1 and Fig. 2.2).

Two types of mafic intrusives occur, namely

1. Kimberlite pipes;
2. An extensive system of dolerite dykes.

The **Mosolotsane Formation** consists of intercalated reddish mudstones and siltstones with fine to medium-grained sandstone and coarse arkosic grits (Bush and Blecher, 1993). An unconformity with the underlying mudstone marks the base of the Mosolotsane.

The **Ntane Sandstone** is synonymous with the Cave Sandstone in the RSA. Moving eastwards from Orapa, this formation is found to lie conformably on the Mosolotsane Formation, then on the older Karoo Formations, and finally on pre-Karoo basement rocks.

The **dykes** have a west-northwesterly strike and are rarely exposed at surface. They are fresh to weathered, fine to coarse grained and seem to have been emplaced along fractures about 140 Ma ago (Bush and Blecher, 1993).

The sedimentary cover of **Kalahari Beds** extends over most of the area and overlies the formations mentioned above. The Kalahari Beds comprise a variably thick succession of aeolian sand, intercalated with calcretes, silcretes and ferricretes. The thickness of the Kalahari Beds, at more that 100 metres in the southwest, thins out towards the Orapa/Letlhakane area.

Structural and tectonic evolution

Reconstruction of the geological structures has relied mostly on photogeological interpretation, airborne geophysics and satellite imagery with limited ground and geophysical survey and borehole information. According to Bush and Blecher (1993) the following structural elements *can be identified:*

- large northwest striking fractures which are prominent along and east of Letlhakane River;
- smaller, closely spaced northwest trending fractures which appear to be a development secondary to the large fractures;
- north-northeast trending fractures which appear all along the Letlhakane river;
- large northeast striking fractures occurring in the southwest of the study area;
- dominant west-northwest trending fractures which most commonly are intruded by dykes;
- east-northeast trending fractures which are not intruded by dykes.

The complex fracture pattern plays an important role in the occurrence of ground water in exploitable quantities. The formation of the different fracture patterns is related to major tectonic uplift. The main result of the tectonic evolution of the study area has been the development of a series of horst and graben structures with a west-northwest trend often bounded by dolerite dyke intrusions which control the occurrence of ground water in the area. (see Fig. 2.2).

The block-faulted Ntane Sandstone is shown in Fig. 2.3 according to geological modelling and contouring of the surfaces of the different formations (Bush and Blecher, 1993). Interestingly, the major structures inferred in the Ntane Sandstone (Fig. 2.4) and in the underlying Mosolotsane Formation, do not coincide. *This could only mean that the tectonic evolution resulting from the structural upheaval and the downshift are from different geological eras.*

3. HYDROGEOLOGY

The properties of the different aquifers are pertinent to the present study and in considering the utilisation and exploitation of ground water by the mines.

The Kalahari Beds hold mainly perched water and can sustain hand-dug wells and shallow ranching boreholes. This aquifer responds rapidly to recharge during heavy rainfall events. It is interconnected with, and has similar piezometric levels to, the underlying basalt and Ntane sandstone aquifers when recovered following cessation of exploitation (Mazor et al. 1977).

The **Stormberg Basalt,** a hard and generally unweathered basaltic lava, acts as a confining or semi-confining layer to the underlying Ntane sandstone and Mosolotsane Formation on account of its low primary porosity. However, due to weathering which developed along fracture zones and secondary fracturing of the basalt, the water-bearing capacity of the basalt has improved. Overall. and also because of its variable ground water quality, this formation is not regarded suitable for exploitation of ground water for the mines on a regional scale.

The contact between the Stormberg lavas and the underlying Ntane sandstone was shown to be an important aquifer, characterised by a metamorphic zone of indurated and fractured material with high permeability.

The **Ntane Sandstone** is the best aquifer in the area because of its relatively high intrinsic porosity and high secondary permeability. However, the permeability of the solid sandstone is low and can only sustain low-yielding boreholes. Significantly higher yields are however encountered where there has been secondary development of fractures due to faulting, brecciation, jointing, and probably also along the contact zones with dyke intrusions. Higher yields are also obtained in the lower fluvial coarse-grained sections. Yields of boreholes drilled into the Ntane Sandstone vary from as little as 0,3 m^3/h to 110 m^3/h and the aquifer reveals the characteristics of a confined to leaky sub-artesian aquifer because of the rapid rise of the water levels from the depth at which water was struck to the general piezometric level. As will be discussed later (see Section 7) the aquifer displays the typical hydraulic response of a fractured aquifer characterised by low storage coefficients derived from the standard interpretation of pumping tests.

The **Mosolotsane Formation** which underlies the Ntane Sandstone is not a good aquifer and low yields and more saline water are encountered. High abstraction from the Ntane Sandstone often results in a deterioration of the water quality due to upwelling of water from the Mosolotsane Formation. The Mosolotsane Formation is therefore not regarded to be viable for exploitation of ground water.

The role played by the numerous dykes traversing the study area is perhaps underestimated. The dykes are regarded to act partially as barriers which are believed to cause steps in the piezometric level. Ground water of differing quality can be found on either side of some dykes. The influence of dykes may have to be reviewed in the light of information obtained from studies of the Karoo formations in the RSA, as well as from dolomite, both of which appear to be fractured aquifers. It seems that the contact between a dyke and the surrounding rocks presents a zone of higher permeability which is capable of tapping water from the low permeability parent rock over large distances and from great depths. Hence the contact zone yields exploitable quantities of ground water. The same may apply to Kimberlite pipes, which may require further examination in view of new conceptual models on the influence of these intrusives on ground water (A. Issar, personal communication).

Table 3.1 Average monthly abstraction (in $m^3 \times 10^3$) from the mine well-fields and the Letlhakane and Orapa pits

	1984	1985	1986	1987	1988	1989	1990	1991	1992
WF 2+3	67	85	90	76	85	92	105	80	81
WF 4	28	25	89	81	65	54	45	35	40
WF 5	130	115	196	183	180	190	176	155	179
WF 6						4	45	110	127
DK 1		75	74	72	95	90	87	80	81
AK 1									20
Total :	225	300	449	412	412	425	458	460	528

Five well-fields have been developed to supply water to the Orapa and Letlhakane mines (see Fig. 2.3). The mean monthly abstraction for 1984-1992 is shown in Table 3.1 (from Bush and Blecher, 1993). The distribution of boreholes with different yields is shown in Fig. 3.1 (after AAC). A clustering of boreholes with higher yields occurs along the Letlhakane river.

In many cases the high yields do not reflect the full potential of the Ntane sandstone aquifer where boreholes have penetrated only a few metres into the Ntane aquifer.

4. ESTIMATION OF GROUND WATER RECHARGE

4.1 Introduction

One of the main objectives of the present Orapa-Letlhakane study has been to test the applicability of techniques of estimating ground water recharge and aquifer storativity - the two most important parameters in the evaluation of ground water potential and aquifer management. Isotopic studies (Verhagen et al. 1974, Mazor et al. 1974, 1977) had demonstrated clearly that recharge was occurring in the area, but no attempt was made at the time to quantify the recharge. A water balance study carried out by Van Rensburg and Bush (1995) confirmed the conclusions based on earlier isotope observations of Verhagen et al. (1974), and Mazor (1974, 1977), that recharge does occur and that it can be quantified in spite of it being very small. The realisation that recharge does take place, as well as its quantification, has a significant impact on the dewatering of, and on sustained water supply for, the mines.

4.2 Methodologies of estimating ground water recharge

To obtain reliable quantitative recharge estimates in semi-arid regions is difficult. Rainfall is low and erratic and is often insufficient to produce infiltration which could reach ground water in excess of the natural evapotranspirative demand. The probability of diffuse recharge is further diminished by a thick overburden of Kalahari sediments. Recharge seems more likely where rain water accumulates in small or larger depressions or via preferred infiltration routes. This implies large spatial variation of recharge and limits the value of methods of recharge assessment pertaining to the unsaturated zone which yield only point values.

Irrespective of its origin, recharge manifests itself as a rise in the ground water level. Reliable interpretation of water level rise is complicated because of the lagged response, the impact of natural losses, of abstraction and of inadequate monitoring boreholes. The storativity of the aquifer is an essential element which cannot be determined reliably because of the dependence of the water-level response on different factors such as recharge, losses and the *effective* porosity of the aquifer. Deriving storativity from the classical interpretation of aquifer pumping tests has proved unreliable in fractured aquifers (Bredenkamp et al. 1994).

An assessment of the different techniques by which rainfall recharge can be estimated, is presented schematically by Bredenkamp et al. (1994). The evaluation of the different methods is largely based on a study of recharge in different aquifers and climatic regions in the RSA, and provides an, admittedly subjective, comparison of the different methods and a rating of the applicability of different techniques.

4.2.1 Direct methods: Unsaturated zone

From this category of methods only the tritium and chloride profiles can be applied with reasonable confidence provided a good areal coverage of profiles is achieved. The tritium profile method determines the rate at which soil moisture has penetrated the unsaturated zone - assuming a piston-like displacement of incoming soil moisture. The chloride profile method is based on the ratio of the chloride concentration in rainfall to that of moisture contained in the soil profile. Both are essentially mass-balance approaches.

Tritium profile method

In the tritium profile method the rate of downward movement of the soil moisture can be derived from the depth to which rainwater from 1962/3 had progressed downwards. 1962/3 rainfall heralds the leading edge of the peak of higher tritium concentrations produced by fall-out from thermonuclear tests. Recharge could be determined by

- assessing the depth of pre-bomb/post-bomb tritium front,
- reconstructing the shape of the tritium profile,
- integrating the tritium content of the soil moisture, related to that of the rainfall.

The basic assumption is that the propagation of the soil water is effectively a piston-like displacement, albeit dispersed to a greater or lesser degree, of the different contributions of the infiltrating rainwater whereby the tritium signature is retained in the soil profile. Smith et al. (1970) who first drew attention to this method, however indicated that bypass of tritium could occur by means of faster flow of infiltrating water along larger pores or pathways in an apparently uniform unsaturated medium. Recent work on the unsaturated zone in the Kalahari (Beekman et al. 1996), and elsewhere (Edmunds and Verhagen 2000), leads to similar conclusions.

The chloride profile, on the other hand, is based on the loss of water vapour from the soil through evapotranspiration. It relates the increase in chloride concentration of rainfall to that obtained in the moisture which is extracted from the soil profile. The reliable assessment of the chloride concentration of rain water can present difficulties (Beekman et al. 1996).

Both the tritium and the chloride profile methods represent point measurements of recharge. The reliability of the overall estimate clearly will improve as more profiles representing the different surface and soil conditions are analysed. Both methods require that a reasonable thickness of soil/sand should be sampled. In the area considered here, not only is the Kalahari Beds soil cover of variable thickness, but sampling penetration could be restricted by calcrete layers.

The chloride profile method will continue to be useful, as chloride aerosol deposition is quasi-constant with time. The usefulness of tritium profiles has diminished because the thermonuclear "peak" is diminishing through radioactive decay, dispersion, and by being displaced beyond the depth of the soil cover.

The tritium profile method produced variable estimates of recharge. Jennings (1974) and Verhagen et al. (1974), obtained a recharge of 18 mm/a from a profile in the central Kalahari (Mabutsane, Fig. 4.1). Verhagen et al. (1979) reported moisture fluxes of between 10 and 20% of the mean annual rainfall in the Kalahari for the years of high rainfall experienced from 1974 to 1976. Foster et al. (1982) having analysed both tritium and chloride profiles in southern Botswana came to the conclusion that it is unlikely that recharge could occur through Kalahari sand cover of more than 4 m. Isotopic studies (Verhagen, 1993) of the *saturated zone*, through the Jwaneng mine well field subsequently established in the same area studied by Foster et al. (1982), showed long-term ongoing recharge of the order of 5 mm/a. This underlines

1) the danger of extrapolating findings from the unsaturated zone measurements on a regional basis and
2) the need for more extensive and longer-term observations on the chloride levels in rain before reliable interpretations can be made.

Gieske (1992) analysed a tritium profile at Matlagatse in the Kalahari sands about half-way between Molepolole and Letlhakeng which indicated that post-bomb tritium levels occur at depths of 10 m in sandy loam soils. An interpretation of further tritium profiles gave reasonably consistent recharge values and agreed well with those determined from the chloride profiles (see Table 4.1). The estimated recharge varied between 8 and 18.7 mm/a. This could be regarded as rather high. The rainfall in this area is higher than that of the Orapa/Letlhakane area, however, and soil conditions may not be quite comparable.

Table 4.1 Recharge values derived from soil moisture flux values obtained by Foster et al. (1982) and reinterpreted by Gieske (1992) based on more recent chloride deposition data.

Site	Depth (m)	Total Chloride (g)	Total Moisture (mm)	Moisture Flux (mm/yr)	Total Tritium (TU mm)	Moisture Flux (Tritium)
B1	6	40	240	2	1600	4
B2	8	64	320	2	5100	13
B3	8	21	480	9	4900	12

The estimates of recharge based on chloride profiles are lower than estimates derived from tritium profiling as was revealed by recharge estimates obtained by Foster et al. (1982) in the region of Orapa. The reliability of the latter recharge estimates has been questioned in the light of mechanisms other than displacement of soil moisture which could account for the penetration of recent rainfall to depths of a few metres. In order to explain significant differences between the recharge obtained from chloride and tritium profiles, Gieske (1992) has reinterpreted the chloride profile results of Foster et al. using more reliable values for the chloride concentration of the input rainfall. This produced comparable results of recharge ranging from 2 to 9 mm/a for the chloride profiles and 4 to 12 mm for the tritium profiles (See Table 4.1).

Allison and Hughes (1978) reported large spatial variations in recharge when applying the tritium profile method in an apparently homogeneous soil overburden. This confirmed that a large number of profiles would have to be analysed to obtain a reliable average value of recharge. They concluded that spatial variability of recharge is probably the greatest obstacle in the determination of a reliable estimate of recharge for a specific aquifer from unsaturated zone observations.

The Kalahari overburden, with its horizons of calcrete and encrustations, produced large variations in recharge derived from chloride profiles, taken along a 5 km long transect in the

Bray area of South Africa (Bredenkamp 1993). The average value for the recharge derived from all the profiles analysed yielded a value of 2,9 mm/a. This compares well with the revised estimates listed in Table 4.1, for areas experiencing similar annual rainfall conditions.

As with chloride profiles, tritium profiles can only be obtained from those areas covered by a reasonable thickness of soil, for which the recharge would generally be lower than for areas covered by a thin overburden, which allows quicker access of water to fissures connected more directly to the ground water reservoir.

Chloride profiles

The chloride profile method was applied only in isolated locations in the present area. Gieske (1992) analysed chloride profiles in the Pitsanyane area which is about 500 km south of Orapa, and arrived at a recharge of 7,4 to 11 mm/a for an average rainfall of 450 mm/a. The chloride profile method had been used successfully by Bredenkamp (1993) in different climatic regions to derive a regional rainfall/recharge relationship (see Fig. 4.1). Recharge values agree quite well with those obtained by Gieske for corresponding rainfall values.

Based on the regional rainfall/recharge relationship (refer to Fig. 4.2) the recharge for the Orapa area which has an average rainfall of about 390 mm/a, is estimated at 3,9 mm/a. This is close to the estimate obtained by Van Rensburg and Bush (1995), which ranges from 2,7 mm/a to 5,4 mm/a. The derivation of the latter value (discussed in Section 5.1) is regarded to be one of the most reliable estimates to date.

The discussed in Section 6 shows that those recharge events which cause the water levels to rise, are those when rainfall exceeds the average monthly value and not necessarily, *as is often assumed*, when intense storms of short duration are experienced. However, the preceding rainfall also plays a role. The chloride profiles sampled in the region of Bray had, in spite of a highly variable overburden, indicated local areas which are more conducive to recharge (Bredenkamp, 1993).

It can be concluded that tritium and especially chloride profiles have been successfully applied to derive recharge, but due to a lack of corroborating evidence the results have previously been treated with suspicion.

4.2.2 Estimation of recharge based on ^{14}C concentrations of ground water

As discussed above, recharge to the sand-covered Kalahari aquifers, especially the Karoo, has long been a controversial subject. Following the early work by Martin (1961), recharge was discounted and the deep-seated ground water was regarded as fossil, a concept reinforced by early radiocarbon measurements (Vogel and Bredenkamp, 1969 and Vogel, 1970). This proposition was challenged in the early 70's, when the first environmental isotope data was produced for the Kalahari in northern Botswana (Verhagen et al., 1974; Mazor et al., 1974;1977). This data showed quite unequivocally that diffuse modern rain recharge was occurring. Since then, ground water development and assessment projects have begun to consider recharge as an important component in resource evaluation and management.

Although qualitative information clearly pointed towards modern recharge, it did initially not seem possible to quantify this recharge. This was largely on account of conceptual difficulties encountered, the most important of which are:

1) with ground water levels standing in the confining basalt and Kalahari cover, does transport of rain recharge into the underlying Ntane actually occur under natural conditions ?
2) what happens to the recharged ground water in the absence of artificial abstraction ?
3) could reliable values of total aquifer porosity be obtained ?

The regional piezometry of the Karoo ground water follows the topography (Fig. 1.2). Furthermore, the aquifers are heavily block-faulted and tend to form compartments (Figs. 2.1,2.2,2.3,2.4). Regional ground water flow is probably restricted. de Vries (1984) proposes that no meaningful recharge has occurred since the last pluvial phase, postulated at some 12000 years B.P. The regional baseline for the resulting north-eastwards drainage from the southern Kalahari is lake Makgadigadi and he ascribes present-day regional ground water gradients to declining heads since the pluvial. It has been pointed out by Verhagen (1990) that present-day piezometric levels lie well below the surface of the now-dry lake, and that there is no known discharge of liquid water. Verhagen (1985) proposed that the balancing mechanism for ongoing recharge should be deep evapotranspiration, a mechanism more recently invoked (Ndiaye et al. 1992) to account for large-scale piezometric depressions in the Sahel. In fact, it was pointed out by Verhagen (1990) that present-day Kalahari regional piezometry shows such depressions.

The spatial and temporal distribution of recharge is another question which is not resolved. Verhagen (1984) postulated at the hand of stable isotope, radiocarbon and hydrochemical observations on ground water of Gordonia, that diffuse recharge in the Kalahari is generated by exceptionally intense and localised rainfall events, outliers in the normal continental convective regime. Such rainfall events, an extreme and recorded example of which is the Uhlenhorst cloudburst in Namibia in 1960 (Schalk 1961), are now found to be much more common than previously believed. These various factors should influence the distribution of recent water in the saturated zone.

In the Orapa area, the Ntane sandstone represents a more or less continuous, confined, dual porosity aquifer. The overlying basalt is essentially a fissure aquifer, which on a regional scale acts as a leaky confining layer for the sandstone. If the ground water in the Ntane would be in consistent regional motion, under the influence of ongoing diffuse recharge, the flow lines could be visualised as shown in Fig. 4.3 (a)

As is discussed above, it is probable that such regional flow is insignificant in the present climatological regime. Isolated recharge events would produce local mounding, which in turn would produce a localised, transient flow system as shown in Fig. 4.3 (b)

Such sporadic recharge events could constitute a regionally averaged long-term diffuse recharge. The net result could be an age stratification which resembles the situation as established in a flowing aquifer subject to steady, diffuse recharge.

Evapotranspirative losses (Verhagen 1985,1990) are likely to be the principal balancing mechanism and should be mainly from the upper layers of the aquifer system. As these involve only water, tritium will be lost. However, the overall mineralisation and total dissolved inorganic carbon (TDIC), which carries the ^{14}C tracing signal, remains in the saturated zone. The loss mechanisms for the tracer are principally radioactive decay which changes this carbon isotope ratio and precipitation as calcrete, which is to first approximation non-fractionating.

The exponential model assumes an exponential increase of transit time with length of flow path. It may or may not apply acceptably to the age distribution in the confined Ntane. As an approximation, the water pumped from a borehole is taken to represent a well-mixed sample of the section of saturated zone penetrated by, and accessible to, the borehole. The mean residence time of this sample is then derived from the ^{14}C value for this mixture, i.e. the sample taken from the pumped borehole. It should be borne in mind that this is a quasi steady-state situation, in which the ^{14}C tracer, introduced with the recharging ground water, eventually diffuses into all the interconnected pores of the aquifer. This process is likely to proceed on a time scale which may be comparable to that represented by the radiocarbon mean life (8270 a).

Regional abstraction from the aquifer due to dewatering/exploitation is a process which invokes responses firstly from the *storativity* of the aquifer, whilst the ground water is effectively confined, as at present. This represents mainly the fractures in the sandstone. When the water level has been drawn down to below the confining layer, the *specific yield* becomes important, i.e. draining of the *effective porosity*. Long-term exploitation involves an increasing hierarchy, initially of major and then of minor fractures (secondary porosity), and a hierarchy of slower responses from the primary porosity (see also remarks by Neumann, Section 7.3). Under confined conditions, the hydraulic response is represented by a storage coefficient, which can be orders of magnitude smaller than the total porosity.

It is assumed that long-term tracers such as ^{14}C are more representative of the *total porosity*. As argued above, the labelling process occurs partially by bulk water transport, partly by diffusion, on time constants probably very long (tens to thousands of years) compared with the periods characteristic of pumping tests.

Support for this assumption is found in the available time-series of ^{14}C for the exploitation of the Jwaneng mine well field (Verhagen, 1993). Considerable differences are observed between the ^{14}C values for water pumped from individual production wells, which individually have remained remarkably constant over a period of close on a decade of major exploitation. This is taken to indicate that the ^{14}C labels not only the more mobile water in the fractures and immediately adjacent pores, which should have been turned over during the period of exploitation, but must have equilibrated into the deeper pores of the sandstone rock matrix.

Environmental isotope data for Orapa has been produced since 1969 (Verhagen et al. 1974, Mazor et al. 1977). Only the data obtained since 1987 will be discussed here (Table 4.2). The object of the latter sampling project was

a) to obtain first strike and deeper samples, which were intended to indicate age stratification and a qualitative indication of recharge and
b) pumped samples from completed boreholes, which would provide information averaged over the saturated thickness penetrated by the borehole.

In the event, it was found that in most instances, ground water was first struck at the basalt-sandstone contact. The low radiocarbon values clearly show that this water is usually rather immobile. Considering the hydrogeological situation of a confined aquifer and Fig. 4.3, this is quite reasonable. At sites where first strike is at the basalt/sandstone contact, it follows that the basalt must be largely impermeable. The radiocarbon value, as measure of turnover time, will depend on whether water is displaced downwards from the basalt in the vicinity of the borehole. A case of clear downwards displacement is EB21 OB 1 (sample OC/O 19) at 89 pMC. The same borehole first struck water at 103 pMC in basalt.

The cases where the first strike at the basalt/sandstone contact gives low ^{14}C values (high residence times) could reflect not only the absence of vertical, but also of horizontal, displacement. This could be taken as confirmation of the absence of significant regional movement of ground water in the Ntane, suggested by the geohydrological situation of the Ntane.

Table 4.2 Isotopic measurements for different ground water samples in the Orapa/Letlhakane area

Sample No	Sample Site	Sample Date	^{14}C pMC	^{3}H TU	$\delta^{13}C$ o/oo	$\delta^{18}O$ o/oo	$\delta^{2}H$ o/oo
OC/O 1	EB 10 first strike 62m	16.08.87	69.3±0.5	0.2±0.2	-8.0	-6.7	
OC/O 2	EB 13 first strike 82m	04.09.87	6.8±0.5	0.1±0.2	-0.1	-5.3	
OC/O 3	EB 13 pump test	17.10.87	7.6±0.5	0.3±0.2	-3.2	-5.1	
OC/O 4	EB 10 pump test	30.10.87	74±0.5		-11.2		
OC/O 5	PB 29 first strike 34m	15.09.87	89.4±0.4	0.0±0.2	-6.8	-5.7	
OC/O 6	EB 16 first strike 176m	25.09.87	34.1±0.7		-5.1	-7.8	
OC/O 7	EB 15 first strike 110m	05.10.87	41.2±0.8	0.5±0.2	-2.7	-6.0	
OC/O 8	EB 15 pump test	07.11.87	18.3±0.6	0.2±0.2	-6.2	-6.2	
OC/O 9	EB 16 pump test	22.11.87	9.8±0.5		-6.6		
OC/O 10	EB 19 flush sample 178.5m	03.12.87	18.8±0.6	0.0±0.2	-7.6	-5.6	
OC/O 11	EB 19 pump test	10.12.87	24.2±1.2		-9.8		
OC/O 12	EB 20	12.08.88		0.9±0.3		-5.8	
OC/O 13	EB 20 OB 1 first strike 80m	18.08.88		1.1±0.2		-4.7	
OC/O 14	EB 20 OB 2 first strike 80m	23.08.88		0.5±0.3		-5.8	
OC/O 15	EB 20 OB 1 mai strike 136m						
OC/O 16	EB 20 OB 2 first strike 80m	23.08.88		0.5±0.3		-5.9	
OC/O 17	EB 21 90m	02.09.88	103.2±1.1	0.5±0.2	-10.0	-5.5	
OC/O 18	EB 21 OB 2 118m	13.09.88	10.6±0.5		-8.5		
OC/O 19	EB 21 OB 1 116m	08.09.88	89.6±0.8	0.8±0.2	-8.7	-5.6	
OC/O 20	EB 22 first strike	18.09.88	26.6±0.6		-8.4		
OC/O 21	EB 21 first strike 90m	02.09.88		0.5±0.2	-10.0	-5.3	
OC/O 22	EB 21 OB 1 strike 143m	08.09.88		0.2±0.2		-6.1	
OC/O 23	EB 21 OB 1 116m	08.09.88		0.0±0.2		-5.7	
OC/O 24	EB 21 OB 1 116m	08.09.88		0.8±0.2		-5.5	
OC/O 25	EB 21 OB 2 first strike 108m	13.09.88		0.0±0.2		-6.3	
OC/O 26	EB 21 OB 2 f strike drill water	13.09.88				-5.3	
OC/O 27	EB 23	15.10.88	17.2±0.5		-6.4	-6.1	
OC/O 28	Marie replacement 83m	01.10.88				-5.5	
OC/O 29	PB 2/4	22.09.88	41.1±0.3		-7.4	-5.9	
OC/O 30	Marie replacement first strike	01.10.88		0.5±0.2		-5.4	
OC/O 31	PB 2/4 drill water	22.09.88				-5.9	
OC/O 32	EB 21 c/dis last hour	11.10.88		0.1±0.1		-6.3	
OC/O 33	EB 23 strike fluv 244m	14.10.88		0.3±0.2		-6.0	
OC/O 34	EB 23 drill water 137m	13.10.88				-5.3	
OC/O 35	PB 2/4 101.5m	22.09.88		1.5±0.3		-5.7	
OC/O 36	EB 23 137m	13.10.88		0.1±0.2		-5.9	
OC/O 37	EB 20 end of c/dis	25.09.88		0.9±0.3		-5.6	
OC/O 38	PB 2/5 100m	27.09.88		0.0±0.2		-5.7	
OC/O 39	PB 2/4 c/dis	03.10.88		0.2±0.2		-5.8	
OC/O 40	EB 22 (OB 1) 96m	07.11.88	42.2±0.5	0.0±0.2		-5.3	
OC/O 41	EB 24 first strike	01.11.88	18.6±0.8	0.3±0.2		-6.1	
OC/O 42	EB 26 first strike	10.11.88		0.3±0.2		-6.2	
OC/O 51	BH 27095 44h on 48 step P1	09.06.92	43.0±0.5	0.3±0.3	-9.8	-6.4	-41.4
OC/O 52	Cattle post near 27095 P2	09.06.92		8.3±0.5		-6.4	-40.6
OC/O 53	BH 27097 20h on crt P3	29.06.92	1.6±0.4	2.0±0.3	-7.2	-6.3	-39.0
OC/O 54	2125 D/K1 P4	30.06.92		0.7±0.3		-7.6	-40.7
OC/O 55	27100 SPM P5	16.07.92	3.6±0.4	0.9±0.3	-8.3	-6.4	-40.7
OC/O 56	27146 42h on 72h CRT P6	17.07.92	1.5±0.4	0.2±0.3	-6.0	-6.9	-43.6
OC/O 57	27141 46h on CRT P7	24.07.92	2.3±0.4	0.6±0.3	-3.3	-6.0	-39.0
OC/O 58	27152 45h on 72h CRT P8	25.07.92	4.5±0.4		-6.5	-7.0	-44.7

The total water column (depth x total porosity) divided by the mean residence time of all the water in the aquifer gives the long-term recharge rate.

$$R = \frac{pH}{8270\left[\left(\frac{A_o}{A}\right) - 1\right]} \qquad \text{eq.4.2}$$

where H height of saturated zone
p total porosity
A measured radiocarbon value
A_o estimated initial radiocarbon value

In order to assess recharge, it is necessary to have acceptable values of the *total porosity* of the aquifer. The porosity of the Ntane was measured for various samples from cores from a number of boreholes at Orapa. The values are given in Table 4.3.

The results for 6 different boreholes (EB series), at various depths, are remarkably uniform with a mean value of 0.22±0.06. Porosity values for boreholes in well field 2 produce a mean of 0.27±0.05.

For the recharge calculations, a maximum porosity value of 0.2 is taken. A minimum of 0.1 is set, assuming that part of the aquifer attenuates the diffusion significantly on the ^{14}C time scale. The only cases considered were for ^{14}C values obtained during pump tests. These will approximate the requirement of a mixed sample from the saturated zone. A borehole with major delivery will furthermore pull in water from a zone of increasing radius, thus generalising any observations beyond the point observation represented by a non-pumped borehole.

The recharge calculations are based on the following:

1. Only the Ntane thickness is taken into consideration, as the porosity of the overlying basalt is assumed to be low in comparison.
2. An estimate is given of the thickness of the *aeolian* sections of Ntane. The remainder is more argillaceous and could contain more immobile water. We have here a further hierarchy of ground water mobility, which is of importance in any consideration of the dynamic response to abstraction. The more argillaceous sections should however still be considered as labelled by the tracer. To assess the limits of the calculated recharge rate, the total and aeolian thickness of the Ntane are employed in the calculation of maximum and minimum recharge figures respectively.
3. Only in crystalline or purely siliceous terrain can one expect an initial radiocarbon concentration in the TDIC of recently recharged ground water approaching 100% of the atmospheric value. The Kalahari Beds in the area of study almost invariably contain calcareous

material. Exchange with, and dissolution of, this material by infiltrating ground water will dilute the biogenic TDIC to values lower than 100% atmospheric:

Table 4.3 Total porosities and permeabilities measured on samples of Ntane sandstone taken at different depths (Gemlab, 1983)

Borehole No.	Depth mBGL	Lithology	Total Porosity %	Permeability m/day
EB 1	54	Siltstone	8	5.1EE-4
	71	Sandstone, f.g.	18	4.3EE-2
	105	Sandstone, f.g.	29	4.5EE-2
EB 3	123	Sandstone, f.g.	25	Impermeable
	132	Sandstone, f.g.	27	4.8EE-3
	145	Sandstone, f.g.	22	Impermeable
	151	Sandstone, f.-m.g	25	8.7EE-2
	180	Sandstone, v.f.g.	22	1.3EE-2
	215	Sandstone, m.-c.g.	18	1 EE-1
EB 4	95	Sandstone, m.g.	26	1 EE-3
	120	Sandstone, f.g.	26	Impermeable
	145	Sandstone, f.g.	27	5.2EE-4
	172	Sandstone, f.g.	18	2.5EE-3
EB 5	59	Sandstone, m.-f.g.	27	2.1EE-2
	114	Sandstone, f.g.	17	Impermeable
	177	Sandstone, f.g.	19	2 EE-4
EB 8	118	Sandstone, f.g.	23	8.9EE-2
	174	Sandstone, f.g.	24	1.1EE-3
	200	Sandstone, m.-c.g.	29	Impermeable
EB 9	131	Sandstone, f.-m.g.	28	2.8EE-4
	180	Sandstone, f.-m.g.	19	8.1EE-4
	203	Sandstone, m.-c.g.	5	Impermeable
f.g. = fine grained				
m.g. = medium grained		Mean	21.9	2.4EE-2
c.g. = coarse grained		Standard Deviation	6.3	3.7EE-2
2185/1000	66.7	Sandstone, f.-m.g.	30	3.4EE0
(W/F 2)	67.4	Sandstone, f.-m.g.	26	2.2EE0
	68.2	Sandstone, f.-m.g.	17	8.2EE-1
	69.8	Sandstone, f.-m.g.	32	3.3EE0
	70.1	Sandstone, f.-m.g.	31	2.9EE0
	85.3	Sandstone, f.-m.g.	28	2 EE0
	91.4	Sandstone, f.-m.g.	27	7.5EE-1
2185/15083	82.6	Sandstone, f.-m.g.	30	3.4EE0
(W/F 2)	93.3	Sandstone, f.-m.g.	27	2.4EE0
2183/150	85	Sandstone, f.-m.g.	17	2.8EE-1
(WF/2)	86.9	Sandstone, f.-m.g.	28	1.6EE0
		Mean	27	2.1EE0
		Standard Deviation	5.2	1.1EE0

$$CO_2 + H_2O + CO_3^{2-} \leftrightarrow 2\,HCO_3^- \qquad \text{eq. 4.3}$$

In this dissolution reaction, the carbon in the dissolved bicarbonate is derived equally from the limestone and the biogenic source. In the extreme case of e.g. a dolomitic aquifer, where the carbonate matrix is fossil (0 pMC), the resulting TDIC may have a value as low as 50% atmospheric. The Kalahari calcrete is constantly being dissolved and re-precipitated. Highly variable ^{14}C values have been measured in Kalahari calcrete (e.g. Verhagen, unpub. data). It is reasonable to assume that TDIC values as low as 50% atmospheric are never reached in infiltrating water in the study area.

As with tritium, atmospheric ^{14}C levels increased due to thermonuclear fallout. From an initial approximately 100 pMC in the late 1950's, southern Hemisphere levels rose to some 160 pMC in the mid 1960's, and have since been declining. At least one case of thermonuclear ^{14}C in ground water (103 pMC; basalt) has been encountered. The highest ^{14}C value in the test pump results is 74 pMC (Table 4.4), the rest being substantially lower. This is taken to indicate that thermonuclear ^{14}C has not yet significantly penetrated into the Ntane aquifer. A maximum range of 90pMC to 70pMC atmospheric is therefore assumed for the initial ^{14}C value of the recharge from which the deep-seated ground water is derived.

The calculated recharge rates are given in Table 4.4 . The "max" values are for $p = 0.2$, A_o = 90 pMC and the total saturated Ntane thickness. The "min" values are for $p = 0.1$, A_o = 70 pMC and the aeolian section of the saturated Ntane thickness only.

Table 4.4 Calculated maximum and minimum average annual recharge for ^{14}C values obtained from pumping tests

Sample No.	Sample Site	^{14}C (pMC)	Aeol. Ntane (m)	Total Ntane (m)	Recharge Max (mm/a)	Recharge Min (mm/a)	Comments
OC/O 3	EB 13	7.6	55	78	0.8	0.3	Thin basalt
OC/O 4	EB 10	74	72	172	21.5	4.5	
OC/O 8	EB 15	18.3	26	122	2.2	0.2	
OC/O 9	EB 16	9.8	6	136	1.7	0.03	No contact
OC/O 11	EB 19	24.2	26.5	26.5	0.6	0.2	
OC/O 51.	Z 7095	43	40	40	2.0	0.7	
OC/O 56	Z 7146	1.5	30	117	0.7	0.09	Saline
OC/O 57	Z 7141	2.3	-	74	0.5	-	Saline
OC/O 58	Z 7152	4.5	5	84	0.7	0.02	Saline

The results obtained for the few cases available are variable, as could be expected for essentially static water in a confined aquifer below a fissured aquiclude, with recharge events probably variable in time and space. The high recharge value for OC/O 4 is ascribed to locally high transmissivity in the aquiclude. Including this value, a mean recharge of 3.7 mm a^{-1} is obtained. Excluding this value the maximum mean recharge for the area is of the order of 1 mm a^{-1}. These means include three values from the southern part of the area where the ground water residence times are high, the water is saline and the $\delta^{18}O$ values are distinctly different from those in the Lethlakane area. Basalt is absent in the south, and the sandstone appears to be indurated, as is observed for exposed sandstone elsewhere in the Kalahari. High residence times are observed even in the Lethlakane area, e.g. EB 13 (OC/O 2,3). The minimum recharge values, which are based on perhaps unrealistically low parameters, are still some 20% of the maximum.

It needs to be stressed that this approach to recharge assessment is independent of whether the ground water is confined by a leaky layer, such as the basalt in this case, as opposed to the hydraulic response to pumping, which of course differs fundamentally from a phreatic aquifer. On the other hand, the isotope data are influenced by local leaky conditions in the confining layers, as opposed to the theoretically invariant values in an isotropic, uniformly recharged phreatic aquifer

4.2.3 Stable isotopes

The concentrations of the stable isotopes oxygen-18 (^{18}O) and deuterium (^{2}H) in ground water reflect the origin of water and the processes to which it had been subjected before the water infiltrated to the saturated zone. The concentrations are expressed in terms of the relative deviation (δ) from the stable isotopic concentration of a sea water standard, expressed as parts per thousand (per mil).

Ground water which has not been affected by evaporation is characterised by $\delta^{2}H$ and $\delta^{18}O$ values which plot on the so-called World Meteoric Water Line (WMWL), shown in Fig. 4.5. This figure shows a comparison of the $\delta^{2}H$ and $\delta^{18}O$ values for surface, rain and ground water in the RSA and Botswana (after Verhagen, 1984). The few samples in the Orapa area for which $\delta^{2}H$ and $\delta^{18}O$ values were measured are also plotted in Fig. 4.5.

Gieske (1992) gives a detailed discussion of the use of stable isotopes and also presents the stable isotope signature of soil moisture extracted from several profiles in the unsaturated zone (Fig. 4.6). Isotopic concentrations are more enriched closer to the surface and lie on the evaporation line. After heavy rains, as had been experienced in 1987/8, the stable isotopic concentrations shift towards the WMWL. This illustrates that evaporative loss processes from the unsaturated zone are usually not reflected in the isotopic composition of ground water. The only significant effect is due to rainfall selectivity, a factor which shifts the isotopic composition of recharge to values more negative than the weighted mean in precipitation. Such results have been obtained by Vogel and Bredenkamp (1969) and Verhagen (1984) in studies of Kalahari ground water in the Gordonia district in the RSA.

Fairly consistent δ^2H and $\delta^{18}O$ values are obtained in ground water of the Orapa/Lethlakane area, irrespective of the radiocarbon residence times of the water, with the more saline, older ground water in the south forming a distinct group. Climatic influences on recharge have therefore not changed significantly over the ^{14}C time scale represented.

5. WATER BALANCE TECHNIQUES

In the 70's and 80's isotopic techniques were the only effective means of assessing recharge. In the 90's, with 30 years of ground water level and rainfall data available, water balance techniques could be applied in the Orapa mining area. The basic theme of the original investigation was to study the response of an aquifer to long-term abstraction. It was realised that pumping tests are of necessity of limited duration, and results show a time dependence of estimates of storativity. Water balance methods based on the saturated volume fluctuation of ground water can be employed to obtain a reliable value for recharge and for aquifer storativity (Bredenkamp et al. 1994).

5.1 Saturated volume fluctuation of the aquifer

The integrated response of the ground water is reflected by the saturated volume fluctuation of the entire aquifer summed by means of a finite-element grid superimposed on the aquifer. The SVF response of wellfield 4 is shown in Fig. 5.1 and has been used to derive the aquifer storativity and the average recharge (Van Rensburg and Bush, 1995).

The water balance equation for a period dT can be represented by the following equation:

$$RE + I - O - Q = S \times dV \qquad \text{eq. 5.1}$$

Where
RE = recharge
I = inflow
O = outflow
Q = abstraction
S = aquifer storativity
dV = change in saturated volume in time dT

Water balance techniques are treated extensively in a manual on recharge (Bredenkamp et al. 1994) and will be discussed only briefly here.

Eq. 5.1 could be used to derive the aquifer storativity and recharge based on certain assumptions which simplify the water balance equation but the assessment of either S or RE is difficult because of the interdependence of these parameters. Under conditions of declining water levels the storativity of the aquifer must be known to be able to derive recharge, and any uncertainty in this parameter will affect the reliability of the recharge estimates. The water balance technique could only be applied to Orapa well fields 4, 5 and 6.

In the first application, the aquifer storativity of all three areas was derived from the three months for which the largest decline in the saturated levels (dV) had occurred (assuming RE = 0 during those periods). Hence the storativity (S) is represented by Q/dV where Q is the abstraction.

Recharge is then obtained by substitution of S in the monthly series of V_i where i indicates the month. The Q/dV ratio yielded an average storativity of 0,00075 in the case of well field 4 and a recharge of 1,4% of the average rainfall. Several more estimates of S and of recharge were derived for the different wellfields and indicated that the recharge could vary between 0,7% and 1,4% of the average precipitation.

The water balance method can only yield a lumped estimate of the recharge and of storativity for the delineated aquifer. The success of water balance methods actually lies in the fact that spatial variations of recharge and of storativity are disregarded. The average values which are obtained for these parameters are usually sufficient for most studies and for the management of an aquifer. Monthly or annual variability of recharge can then be obtained from rainfall/recharge relationships. Bredenkamp et al. (1994) have indicated that the recharge which has a measurable effect on ground water levels is related to the average rainfall over several years. The short-term (monthly) variability of recharge therefore does not appear to be very important.

5.2 Recharge derived from periods of equal volume

Recharge can be considered as being equal to the abstraction over periods for which the aquifer volume has recovered to the same value it had previously attained, hence dV = 0 in eq. 5.1. The recharge pertaining to the each of these periods of equal volume can be related to the corresponding rainfall, with a lag of 4 months applied in the case of wellfield 6. Van Rensburg and Bush (1995) had found that the water levels of wellfield 6 clearly respond with a lag of 4 months to an anomalous rainfall event. Such a lag did however not apply in the case of wellfields 4 and 5.

According to Fig. 5.2 the annual recharge (RE) in relation to rainfall (Rf) in the case of wellfield 4 is:

$$RE = 0.0125*(Rf + 92) \qquad \text{eq. 5.2}$$

The constant lateral recharge component is 0.0125* 92 = 1,15 mm, yielding a total recharge of 6mm/a. This could indicate the effect of a constant cross boundary flow but could also be due to an incorrect derivation of dV due to an insufficient number of observation boreholes from which reliably to reconstruct the saturated volume fluctuations of the aquifer. The constant recharge could also have been caused by a delayed response to preceding rainfall. For this reason a rainfall/recharge relationship employing cumulative rainfall departures is preferred (see Sect. 6). The recharge from the rainfall is equivalent to 4.8 mm/a for an average rainfall of 390 mm.

Table 5.1 Comparison of SVF-interpretations to derive recharge and aquifer storativity for well-field 6.

Method	Recharge Estimate (mm/a)	Recharge as % of rainfall	Aquifer storativity
Change in Saturated volume fluctuation	4.3 5.4 3.75 2.7	1.1 1.4 0.96 0.69	0.00036 0.00046 0.00032 0.00022
Q vs dV relationship			0.00114 0.00126 0.00081 0.00070
Equal volume	Only recharge plus inflow for the pit area could be calculated - 900 000 cub m/a		
CRD method	0.0125(CRD-250) i.e. 5,6 mm/a	1.11	
SVF Letlhakane mine			0.00064 0.001 0.00069

5.3 Adapted Hill method

By means of the adapted Hill method which assumes a linear relationship between the abstraction and the rate of change in the saturated volume fluctuation, both S and recharge can be obtained:

$$dV = \frac{1}{S}(Q + RE) + \left(\frac{I - O}{S}\right) \qquad \text{eq. 5.3}$$

where it could be assumed that I - O = 0. Hence eq. 5.3 shows linear dependence between dV, and Q, with RE = Q if dV = 0.

In the case of wellfield 6 both recharge and aquifer storativity were obtained by Van Rensburg and Bush (1995) as can be seen from Table 5.1.

It has been proven in fractured aquifers, such as the Ntane sandstone and the basalt, that pumping tests do not yield reliable estimates of aquifer storativity (Bredenkamp et al. 1994). A discussion of how more reliable estimates of storativity can be obtained is covered in Sect. 7.

6. CUMULATIVE RAINFALL DEPARTURE METHOD

Cumulative rainfall departures (CRD), which represent the accumulated departure of the rainfall from the long-term average precipitation (Bredenkamp et al. 1994), has been proved to mimic ground water levels remarkably well in the more humid areas.

6.1 Normal CRD relationship

The ${}_{av}^{1}CRD$ values are usually determined from the following equation:

$${}_{av}^{1}CRD_i = \left(Rf_i - Rf_{av}\right) + {}_{av}^{1}CRD_{i-1} \qquad \text{eq. 6.1.1}$$

where ${}_{av}^{1}CRD$ = the cumulative rainfall departure for month i
Rf_i = rainfall for month i
Rf_{av} = average rainfall for total period of investigation

Positive values of Rf_i - Rf_{av} correspond linearly to the recharge occurring in a specific month and the average of these values (negative values assumed to be zero) is proportional to the average recharge:

$$RE_{av} = \frac{p}{n}\sum_{i=1}^{n}\left(Rf_i - Rf_{av}\right)_{pos} \qquad \text{eq. 6.1.2}$$

where p = coefficient representing the recharge
n = total no. of months
pos = positive values only.

The equivalence between the ground water level response and the CRD series has been validated by Bredenkamp and Botha and is discussed in the manual (Bredenkamp et al. 1994). The similarity between the CRD series and the water level response implies a linear correspondence which can be represented by the following expression:

$$V_i = a.\ CRD_i + b \qquad \text{eq.6.1.3}$$

Where

$a = p/S$
$p = RE_{av}/Rf_{av}$
$S =$ aquifer storativity
$b =$ constant.

The recharge and aquifer storativity could be derived by using the natural fluctuations of the ground water levels to obtain the integrated saturated volume fluctuations ($SVF_{natural}$). Pumping has an additional impact on the ground water levels and its effect has to be eliminated before the natural response can be reliably interpreted.

As the recharge in the area of investigation is low and the storativity of the aquifer uncertain, the relationship indicated in eq. 6.1.2 cannot be used to assess recharge. Conversely, the same applies when deriving the storativity of the aquifer using unreliable estimates of recharge.

According to Van Rensburg and Bush (1995) there is a lag of about 4 months before the ground water level responds to a specific signal in the normal CRD series. This lag could be related also to the recharge derived from flood events in the Letlhakane River.

6.2 Modified CRD relationship

A modified CRD series, which relates the average rainfall over a few preceding months to the average over several years (long-term memory of the system) was shown to mimic the ground water level response even closer (Bredenkamp et al. 1994):

$${}^m_nCRD_i = \frac{1}{m}\sum_{j=i-(m-1)}^{i} Rf_j - k.\frac{1}{n}\sum_{j=i-(n-1)}^{i} Rf_i + CRD_{i-1} \qquad \text{eq.6.2.1}$$

where

k = the proportionality factor denoting natural conditions if $k=1$ whilst $k>1$ indicates that pumping has affected the system
m = the number of months denoting the short-term memory
n = the number of months denoting the long-term memory of the system

The short-term memory of the system, which is related to the average rainfall over m months, seems to be characteristic for an aquifer type and can vary from one month to several months.

A one-month short-term memory is typical for the Karoo aquifer in the southern Free State of the RSA which is covered by a thin a layer of soil or calcrete. A short-term memory of 1 - 9 months has been found to apply in the case of dolomitic aquifers in their response to rainfall recharge. Short-term memories of several months are probably related to the attenuation induced by a substantial soil overburden, delaying through piston-like displacement the effect on ground water levels. The long-term memory (n-months) controls the average rate at which losses from the system occur. These losses vary slightly and change in relation to the variation of the average rainfall over n months, which is related to the periodic variation of above and below average rainfall.

The degree of correspondence between the CRD for different values of m and n and the ground water level status (as is reflected by the integrated saturated volume fluctuation of the aquifer, V_i) is indicated by the correlation coefficients plotted in Fig. 6.1. It appears that

- for n = 36 correspondence is best, and the correlation coefficient increases as m increases from 1 to 12 months, with the highest correlation coefficient r = 0,86
- for n = 60 the correlations are poorer and decline as m increases from 1 to 12 months.
- the correlations decrease even more for n = 96 months with the lowest correspondence for m =1 but improving slightly for m = 2 to 12.
- the lowest correlations occur when n = 120 months and m = 1 to 3 months but for m = 4 to 12 months the correlations again improve slightly.

Thus in all cases, except for n = 60 months, the correlation improves if m increases from 1 to 12 months. The reaction of the ground water levels therefore conforms more closely to the average rainfall over 12 months than to rainfall over a shorter interval. This is a clear indication of the integrating effect of the soil overburden, which acts as an intermediate reservoir which gradually releases the soil moisture to effect recharge to the aquifer at greater depth. According to the CRD relationship (for which m<n), the losses from the system are most closely related to the average rainfall over a period of 36 months preceding a specific month, whereas the effective rainfall is the average over 12 months.

The poorer correlations e.g. for n = 60, 96 and 120 months are interpreted as a gradual shift from an in-phase response to one that is out of phase with the natural processes effecting recharge.

6.3 Incorporation of abstraction and examination of the effect of lagged response

The effect on the CRD values when an aquifer is being pumped can be inferred by incorporating the abstraction as part of the coefficient k in eq. 6.2.1 (Bredenkamp and Botha, 1993). The value of k yielding the best correspondence between the measured and simulated water level responses can either be obtained by regression or, if the abstraction is known, can be calculated from the expression:

$$k = 1 + \frac{Q}{AREA}.Rf_{av} \qquad \text{eq. 6.3.1}$$

where Q = abstraction and AREA = the aquifer area.

Substituting the new value of k back into eq. 6.2.1 allows one to predict the effect pumping would have on the water levels. The abstraction can either be regarded as constant (k = constant) or as a variable component depending on the abstraction. In the latter case the values of k should be adjusted according to the length of the particular long-term period.

Examining the SVF response of wellfield 6 according to the CRD method reveals that the value for k obtained by regression, and which yielded the best fit, was k = 1,022. This assumes a constant rate of abstraction. The impact of a constant rate of abstraction on the CRD series is that the CRD fluctuations would still correspond to the variation caused by the rainfall, but CRD values would become more negative indicating a progressive decline of the water-levels.

By incorporating k into the CRD series for Orapa/Letlhakane the correlation between the observed water-levels and the CRD series improved from 0,86 (Fig. 6.2) to 0,92. The small incremental value of k (Δk = 0,022) stems from the fact that the area of influence is large. For a fractured aquifer the area of influence could be large as had been indicated for dolomitic aquifers (Bredenkamp et al. 1994). However, dykes of lower permeability could limit the hydraulic response to a smaller area. The area of influence could be large in the case of the block-faulted Ntane sandstone and Stormberg basalt aquifers which occur in the region of investigation.

A lag between the short and long-term memories of the aquifer system was incorporated to ascertain if it would improve correspondence between the CRD series and the integrated water-level response. As is shown in Fig. 6.2, the highest correlation occurs for a lag of 4 - 5 months (eq. 6.2.1).

Incorporating the average rate of abstraction the effective area of the aquifer can be calculated from eq. 6.3.1 as 24 km^2. However, it should be possible to infer the true effective area of the aquifer by varying the area in eq. 6.3.1 assuming that the highest correlation coefficient would correspond to the real area of influence. Fig. 6.3 indicates how the correlation coefficient changes when the area of influence is varied. Rather surprisingly it turned out that the correlation coefficient continues increasing as the area is reduced, and the highest correlation is obtained for AREA < 1 sq km. The reason is that because of the small recharge, pumping dominates the water-level response. Hence the water-level response, represented by the SVF fluctuation, could be best fitted by a straight line. The impact of variable recharge becomes less significant because of it being related to the average rainfall over several years (see Sect. 6.4).

If it is argued that the appropriate area of the aquifer would yield the largest improvement of the correlation coefficients it seems that the effective area would be some 30 sq km. This corresponds to a 3 km radius of influence around the Letlhakane pit. It may be possible to check if this radius corresponds to the minimum distance for zero drawdown from pumping tests.

6.4 Some implications of the CRD response of wellfield 6

Aquifers examined as part of the study on recharge (Bredenkamp et al. 1994) yielded the best correspondence between the observed SVF response and the CRD series for an integrating period m < n. As can be seen from Fig. 6.2 this also appears to be the case in wellfield 6 with m = 12 and n = 36 yielding the highest correlation.

It is implied from eq. 6.2.1 that the monthly recharge is determined by the difference between the average rainfall Rf_{av} which is 28,7 mm/month, and the loss in a specific month. The loss is proportional to the average rainfall over the preceding 36 months. Therefore the effective recharge which controls the response of the ground water level would be negative if the average rainfall over the preceding 36 months had been higher than the long-term average, and would cause water levels to decline. Although it seems hard to conceptualise such a response in hydrological terms, the following tentative explanation is offered as the mechanism applicable to more arid regions where the evapotranspirative losses are controlled by the soil moisture conditions sensed by the plant roots in the shallow soil zone. In this analysis, it is presumed that the rate of transpiration of the vegetation, acting as a biological pump, is controlled by soil moisture conditions prevailing over the last 36 months. If above average rainfall conditions are experienced during this period, vegetal activity - which is determined by the soil moisture conditions in the soil zone - would be higher. This would result in a higher rate of evapotranspiration, with relatively less water reaching the saturated zone. When the rainfall over the preceding 36 months is below average the transpiration of the plants will diminish and recharge from subsequent rainfall events will be more effective. Such a mechanism had been proposed by Verhagen (1984) to explain isotopic data for ground water in the Gordonia area, south of the Kuruman River, in terms of enhanced plant development during periods of above-average rainfall inhibiting diffuse recharge.

The soil moisture losses vary proportionally to the average rainfall over the preceding 36 months, causing the ground water levels to respond out of phase with the rainfall. Van Rensburg and Bush (1995) have however shown that close to the Letlhakane river, water levels definitely respond to rainfall with a lag of 4 months. This may be related to the thinner Kalahari overburden along this stretch, but may represent only a portion of the total recharge, superimposed on a steady-state recharge component. This is supported by the rainfall/recharge relationship derived from the equal volume method (see eq. 5.2).

Further work or continued observations at least extending over another wet cycle, is required to investigate the apparent anomalous behaviour of recharge during a wetter period.

6.5 Interchanging the short-term and long-term memory of the system

An alternative analysis of the response of wellfield 6 shows that the correlation coefficient improves if m > n. The highest correlation coefficient (r = 0,93) is obtained with the CRD relationship if n = 36 months and m = total period of rainfall record (see Fig. 6.4).

This implies an inverse relationship i.e. eq. 6.1.3 changing to

$$V_i = -a.CRD_i + b \qquad \text{Eq. 6.4.1}$$

Therefore, according to eq. 6.2.1 the recharge is now related to the average rainfall and the losses are determined by the rainfall over the short-term memory. Such a relationship would be hard to conceptualise in hydrological terms and it seems more likely that the response is caused by a delay between the CRD and the water levels. In a recent study (Bredenkamp 1999) it was found that the best correspondence is achieved for a lag of 14 months with m=12 and n= total length of rainfall series, and incorporating the monthly abstraction in the k factor. This yields

$$V_i = -a.CRD_{i+14} + b \qquad \text{Eq. 6.4.2}$$

A correlation coefficient of 0,99 was achieved and the excellent match between the observed and simulated water levels is shown in Fig. 6.5.

6.6 Determining the aquifer recharge from the CRD series

The following regression fit was obtained (Van Rensburg and Bush, 1995) based on the CRD relationship with a lag of 4 months:

$$RE = 0{,}0125*(CRD - 250) \qquad \text{Eq. 6.5.1}$$

or

$$RE = 0{,}0125*CRD - 3{,}125 \qquad \text{Eq. 6.5.2}$$

This yielded a recharge of 1,11% of rainfall in excess of the threshold value. For the investigation period the recharge amounts to 5,6 mm of 501 mm rainfall i.e. 1,11% of the rainfall. For average rainfall conditions (390 mm/a) the average annual recharge would be 1,7 mm/a.

According to the improved CRD regression (eq. 6.2.1) and incorporating the abstraction in the k-factor, the best simulation value (Cor. Coef. = 0,99) for the recharge coefficient is 0,0125 and an aquifer storativity of 0,0035, with water levels lagging the CRD by 14 months. The excellent fit between the observed and simulated water level fluctuations is shown in Fig. 6.5. An aquifer storativity of 0,0035 which was derived from Fig. 7.1, yields a recharge coefficient of 0.0125. The average recharge for 390 mm rainfall is therefore 4,8mm/a.

7. DERIVATION OF AQUIFER STORATIVITY

7.1 Relationship of discharge with change of storage

The integrated fluctuation of the saturated volume of the aquifer in wellfield 6, for each month (SVF_i) which was derived by Van Rensburg and Bush (1995) has been examined to infer the storativity of the aquifer. An increased rate of decline is evident over the period 6/1990 to 6/1991 (Fig. 6.4), but in the subsequent period up to 12/1992 the rate of decline had decreased. From the steepest rates of declining water levels Van Rensburg and Bush (1995) have inferred the aquifer storativity $S = Q/dV$ assuming recharge to have been zero. This yielded a storativity ranging between 0,0002 and 0,001 which seems to be too low.

7.2 Analysis of pumping test data from Orapa

Many pumping tests have been carried out in the Orapa/Letlhakane area. Deriving aquifer storativity (S) according to classical methods gives incorrect results. This was first concluded from pumping tests performed on dolomitic aquifers, but similar results were obtained for the Karoo aquifer of the southern Free State (Bredenkamp et al. 1994).

The observed value of S declines the further an observation borehole is situated from the pumped borehole. On a log-log scale, values of S fall on a straight line when plotted against distance, as can be seen in Fig. 7.1. In the case of dolomitic aquifers the true value of S was inferred from an empirical line also indicated in Fig. 7.1 representing the actual values of S derived from water balance methods.

Digitising pumping test data is a tedious process, and it would have taken a long time to examine all the pumping tests as to their representativeness. According to K. L. Morton (personal communication) all pumping tests in the Orapa area show similar behaviour. For some pumping tests only one observation borehole was available, but mostly none at all. The tests for boreholes shown in Table 7.1 were the ones re-examined. It should be noted that small errors might have been introduced when the drawdowns were read off graphs, as the original measurements were not available

Table 7.1 Boreholes selected to re-interpret pumping test data according to a new method.

Borehole No.	Type	Distance (m)	Pumping Rate (m^3/d)	Comment
Test 1				
Z7188	Pumping well		1440	
Z7190	Observation well	50		
Z7089	Observation well	1000		Only three observations
Test 2				
Z 7097	Pumping well		960	
Z7096	Observation well	1500		
Z7098	Observation well	50		
Z7099	Observation well	50		

The pumping tests were analysed according to the methods of Theis (unsteady-state for a confined aquifer), Walton (unsteady-state for a semi-confined aquifer) and Moench (double porosity model for a fractured layer). In all three cases the pumping test data were fitted to the relevant analytical equations using the Marquart inverse technique. The results can be seen in Table 7.2.

In both tests, the transmissivity values (T) obtained from the different methods, are fairly consistent. However the coefficient of storage (S), shown in Fig. 7.1, declines as the distance to the observation borehole increases. Interpretations according to the Moench method in the second test, give consistent results for the storativity of the *fissure* system. The results for storativity of the *block* system produce the same decline as the distance between the pumping well and the observation hole increases.

Table 7.2 Parameters obtained by usual interpretation of pumping test data using a selection of standard methods.

		Test 1			Test 2			
		Z7188	**Z7089**	**Z7190**	**Z7097**	**Z7096**	**Z7098**	**Z7099**
		Pump BH	*Obs BH*	*Obs BH*	*Pump BH*	*Obs BH*	*Obs BH*	*Obs BH*
	r (m)		1000	50		1500	50	50
Theis (Hydrocom) Morton, 1992	T	89	180	88	12	28 no fit		4.3
	S	$2x10^{-4}$		$2.3x10^{-4}$	$8.6x10^{-1}$	$1.6x10^{-5}$		$1.4x10^{-4}$
Theis (inverse)	T	84	[*]	73	8	18.8	12.9	[**]
	S	0.3	[*]	0.3	$7.9x10^{-3}$	$2.4x10^{-5}$	$2.0x10^{-4}$	[**]
Walton (inverse	T	90.9	[*]	72.7	8.1	28.4	13.2	[**]
	S	0.3	[*]	0.3	$7.5x10^{-3}$	$2.5x10^{-5}$	$2.0x10^{-4}$	[**]
	R/L	[***]	[*]	$5.0x10^{-2}$	$4.7x10^{-8}$	0.35	[***]	0.12
	L	[***]	[*]	1000	$2.1x10^{7}$	4290	[***]	416
	c	[***]	[*]	13751	$5.4x10^{13}$	649336	[***]	42466
Moench (AQTESOLV)	K	$1.19x10^{-3}$	[*]	$1.1x10^{-3}$	$4.9x10^{-5}$	$4.4x10^{-4}$	$1.7x10^{-4}$	$1.1x10^{-3}$
	Ss	0.127	[*]	$4.61x10^{-7}$	$1x10^{-8}$	$3.9x10^{-7}$	$8.65x10^{-7}$	$2.9x10^{-7}$
	K'	64.6	[*]	42.4	2.43	2.7x10-5	1.18x10-4	52.8
	Ss'	0.128	[*]	$6.39x10^{-6}$	$5.19x10^{-2}$	$3.97x10^{-7}$	$3.55x10^{-6}$	$6.22x10^{-6}$
	Sf	0	[*]	0	7.1	100	81.3	0
	Sw	0	[*]	100	0.54	31.9	0	100

[*] Too few data points for a reliable result
[**] Cannot obtain a good fit
[***] Confined conditions (L=infinity and c=0)

The parameters used in the different methods are:

T = Transmissivity
S = Coefficient of storage
L = Leakage factor
c = Hydraulic resistance of semi-pervious layer
K = Hydraulic conductivity of fissured system
S_S = Specific storage of fissure system
K' = Hydraulic conductivity of block system
S_S' = Specific storage of block system
S_f = Dimensionless fracture skin
S_w = Dimensionless wellbore skin
R = Recharge
r = Distance

Hand-fitted lines for the different tests show the relationship between S and r. These lines are referred to as "pumping test lines". As can be seen these "pumping test lines" are reasonably parallel for a specific type of aquifer. The Orapa pumping test results conform best to the slope of the Karoo formations in the Free State for which an S value of 0,004 has been obtained from water balance interpretations. For the latter aquifer the real S value is inferred from the intersection with line AB regarded to represent the real S value of the particular aquifer. According to this method an S value of 0,0035 can be inferred for Orapa. This value is higher than the value determined by Van Rensburg and Bush (1995) having optimised the response of the aquifer by means of a dynamic model of the entire aquifer.

For the dynamic simulation the aquifer was divided into five zones with different transmissivities and storativities. A comparison of the S values in relation to that of the relevant zone is shown in Table 7.3. The higher aquifer storativity would correspond to a lower percentage recharge than obtained from the water balance method (Van Rensburg and Bush, 1995).

Table 7.3 Transmissivity and aquifer storativity values used in a dynamic simulation of the Orapa/Letlhakane aquifer (after Van Rensburg and Bush, 1995).

	Transmissivity T (m^2/d)		Storativity S	
	Initial Value	Optimized	Initial Value	Optimized
Zone 1	40	29,81	0,00054	0,000681
Zone 2	40	8,00	0,00054	0,002678
Zone 3	40	68,98	0,00054	0,000345
Zone 4	40	127,02	0,00054	0,001208
Zone 5	40	68,50	0,00054	0,000133

7.3 Discussion

Professor Neuman from Tucson, Arizona who is renowned for his work on fractured systems, expressed an interest in the phenomenon of declining S values with distance. Having been presented with the South African results, he volunteered an explanation for the phenomenon:

"Consider the rock to consist of nested storage "reservoirs" comprised of different scale fractures. On one end of the spectrum are a few large, permeable fractures occupying a small relative rock volume which therefore has small porosity and storativity values. On the other end are many small, low-permeability fractures occupying a large relative rock volume which therefore has large porosity and storativity. Let us, for a moment, consider only these two end members. 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 a sizeable local pressure gradient between the small and large fracture reservoirs. Hence S is large. Far from the pumping well, the pressure gradient between the two reservoirs is relatively small. Therefore, water release from the small to the large fractures occurs very slowly. Most of the initial measurable drawdown (in the large fractures) is associated with water release from storage in these same fractures. Therefore, S is small.

With time, local pressure differentials between the reservoirs stabilise and flow everywhere within a given radius approaches a steady radial pattern. Therefore, I would expect S everywhere within this radius to approach a uniform value representing both reservoirs. However, as the flow pattern now is essentially established and close to steady state (even though absolute pressures may continue to decline), standard pumping tests may not reveal this fact: the flow is sensitive to L only at early time. I therefore think that it is important to look at the time behaviour of your data.

If there were only two reservoirs with very different S values, log-log time-drawdown curves close to the pumping well would exhibit a familiar dual-porosity time inflection (of the kind analysed by me for unconfined aquifers). However, if there is a continuous local range of T and S values, such inflection would not be seen. The early log-log time vs drawdown behaviour would then look just like a regular Theis curve. Only long pumping tests would reveal deviations from this curve (unfortunately, storage effects on late behaviour are usually masked by large-scale heterogeneities and boundary effects). Your data suggest to me the existence of such a hierarchy. If so, this is quite exciting for the following reasons:

Chris Barton of the USGS in Denver has found that fracture networks worldwide, in a wide variety of rock types, on a very broad range of scales, form nested sets (or hierarchies) having near-fractal geometries with a relatively narrow range of fractal dimensions. As you may know, I found on the basis of tracer test data worldwide that, on scales from 10 cm to 3.5 km, permeabilities exhibit (random) fractal properties and can be thought of as a hierarchy of nested fields with systematically varying statistical properties (correlation and variance). Just today, I am sending a paper for possible publication in GRL where I quote independent and direct evidence (permeability and transmissivity rather than tracer test data) to support my previous conclusion on scales from 10 cm to 45 km. I further show theoretically, and quote some evidence, that this implies a systematic increase in block permeabilities with block size in 3-D; no systematic change in 2-D; a systematic decrease in 1-D. Chris and I have just presented these results at a symposium devoted to fractals during the recent GSA meeting in Boston (opened by Mandelbrot and closed by the father of chaos theory, Lorentz).

Your data suggest to me that perhaps what you are seeing is yet another angle of the same phenomenon."

These remarks by Prof. Neumann, are in agreement with the analysis of the isotope data (Sec. 4, above) and with tentative statements regarding the similarity in behaviour of different fractured aquifers as reported by Bredenkamp et al. (1992) and Bredenkamp et al. (1994). It was postulated that the general uniformity in the behaviour exhibited by pumping tests provides evidence that the fractures in all of the aquifers tested probably conform to the fractal features of hard-rock aquifers in general. The Orapa data also conform to this behaviour.

It is clear that interpretations of all suitable pumping tests should be revised according to the new method, and would in future have to be applied to all fractured aquifers. S values obtained from pumping tests would have to be compared with estimates of storativity based on water balances to validate the empirical line used to derive the real storativity of a fractured system. In this respect the present study has produced a significant result which is important in understanding the hydraulic behaviour of these aquifers.

8. CONCLUSIONS

It is obvious that the quality of data available for water balance estimates of recharge and aquifer storativity is not as good as had been assumed at the outset of this study. Nevertheless, the water balance methods have provided consistent estimates of average recharge, but not of storativity. The application of the equal volume method is regarded to be reliable over the long term although the SVF response over shorter intervals may be due largely to a hydraulic response and not to water balance adjustments.

The best estimate of aquifer storativity of Orapa was inferred from the revised interpretation of pumping tests (S = 0,0035). The average recharge according to eq. 6.5.1 is about 4,8 mm/a. It could well be that much of this recharge is derived from the Letlhakane river during periods of flooding and that in the rest of the area the recharge is smaller. This is in accordance with the model applied by Van Rensburg and Bush (1995), and the results obtained from ^{14}C residence time considerations.

Although the chloride and tritium profiles indicate that recharge through the overburden does take place, the recharge arriving at the saturated zone is small. Evidence of this recharge is seen in the ^{14}C values observed in (confined) ground water.

Higher evapotranspirative losses from the aquifer appear to be in phase with periods of high average rainfall over 36 months preceding a specific month. Hence, strange as it may seem, recharge appears to be optimal during periods of drought (i.e. the 36 month rainfall being less than the long-term average). This is a phenomenon observed at the hand of isotopic observations in the Gordonia District of South Africa (Verhagen, 1984) and was ascribed to changing vegetal demand. Using an inverse CRD relationship, there appears to be a lag of 14 months between the rainfall and the water level responses. These different interpretations, and the underlying mechanisms, could be the subject of fruitful further investigation.

Environmental isotope measurements have again proved their value in ground water resource evaluation. Reconnaissance sampling provides qualitative information on ground water dynamics and origins. The great advantage of isotope measurements is that they do not rely on long-term observations, as temporal variations in isotope input values and in recharge are integrated in the saturated zone. Sampling provides a snapshot of the system. More quantitative information can be obtained where other parameters, such as aquifer porosity and saturated zone thickness are known. A range of values for recharge of 1 - 3.7 mm/a was obtained for the Orapa/Letlhakane area, conforming to the maximum CRD estimate of recharge (4.8 mm/a) involving a storativity value of 0,0035. This is quite an acceptable value for S of the (confined) Ntane sandstone, as the measured total porosity of sections of this aquifer is well in excess of 0,20.

The modified CRD method for which $m>n$ (CRD) initially provided the best simulation of the aquifer response to both recharge and abstraction. However, incorporating a lag of 14 months, a very good simulation has been obtained for $m = 12$ and n = total length of rainfall series. Using a value of $S = 0.0035$ the recharge coefficient is 0.0125. This agrees with the results obtained by Van Rensburg and Bush (1995). However the CRD method would not allow the simulation of water-level responses at individual boreholes, which can be done by a dynamic model as had been applied by Van Rensburg and Bush (1995).

The rating of the different methods which could be used to estimate recharge remains a subjective evaluation and is dependent on the availability of data on some critical parameters. For example, in the case of estimating recharge using ^{14}C or ^{3}H measurements, the aquifer porosity and saturated zone thickness need to be known.

The application of methods to obtain the short-term variability of recharge (eg. recharge per month) fails totally because of the smoothing of recharge variations by the thick vadose zone and the shallow Kalahari Beds aquifer. This could explain the apparent contradiction between the concept that only exceptionally intense rainfall events contribute to recharge, and the ability of hydrograph-based methods to observe them. The rating however suggests which of the methods could be applied for aquifer conditions corresponding to that of the Kalahari in the

Orapa area.

Meeting the objectives

The value of an integrated approach has been demonstrated and the estimates of recharge based on the water balance approach are regarded to be quite reliable. This value (1,75-4.8 mm/a) compares reasonably with the range of values obtained from the ^{14}C assessment (1-3.4 mm/a). These in turn correspond with values estimated on the basis of chloride profiles, tritium profiles and the regional rainfall/recharge relationship.

Storativity values were derived from the modified interpretation of pumping tests. One of the more significant results of the study is that the hydraulic response of the aquifer (S = 0.0035) conforms to that of the Karoo aquifer in the southern Free State for which an average storativity of 0,004 was obtained by Kirchner et al. (1991).

The study has also shown that the classical interpretation of pumping tests to derive storativity should be interpreted according to the new method (Bredenkamp et al. 1994). Meaningful pumping tests have to be carried out with two observation boreholes. As more pumping test data become available it could be reinterpreted using the similarity in response (S vs distance) to derive a more representative S for the aquifer.

The quantitative interpretation of ^{14}C measurements is dependent on reliable information on porosity and aquifer thickness (Verhagen et al. 1991; Verhagen, 1999). Samples should be taken from pumped boreholes, which ensures that as extensive a volume as possible of the aquifer is being addressed. The minimum requirement for confidence in such assessment is a pumping test. More reliable results would be obtained from boreholes in constant production. Samples from producing well fields were mooted, but did not materialise during the project. These would be of extreme importance, especially those which were sampled in the early 1970's and are still in production. As the ground water in the Ntane is assumed to be near stationary under natural conditions, this 25 year artificial displacement could be most revealing in terms of the vertical movement of water constituting induced recharge. Environmental isotope measurements on operating well fields are therefore highly recommended.

Most of the aims set for the revised project have been achieved and the authors are of the opinion that the report has contributed to a better understanding of fractured aquifers and their effective response to recharge and abstraction.

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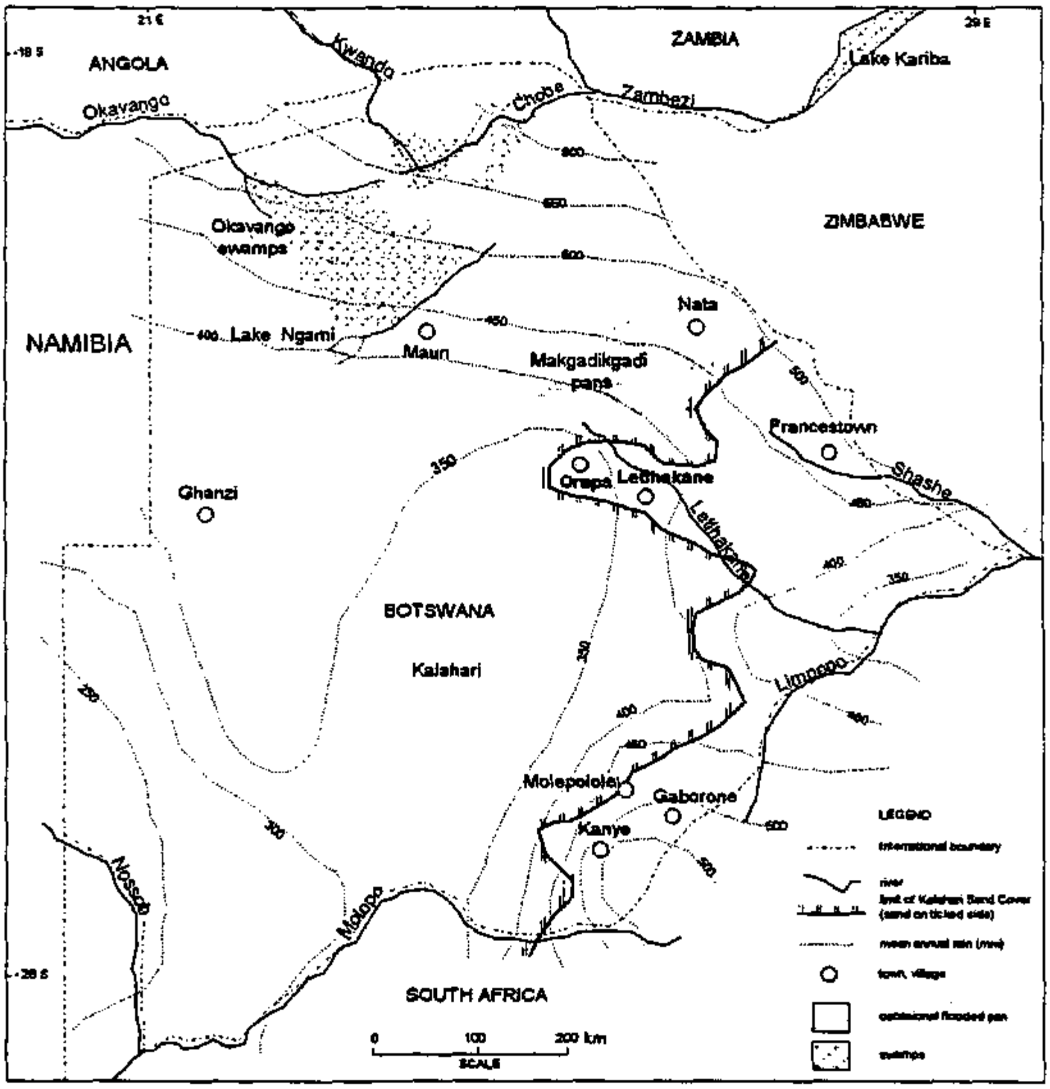

Fig. 1.1 Map showing Orapa and Letlhakane which were the main focus of the groundwater study.

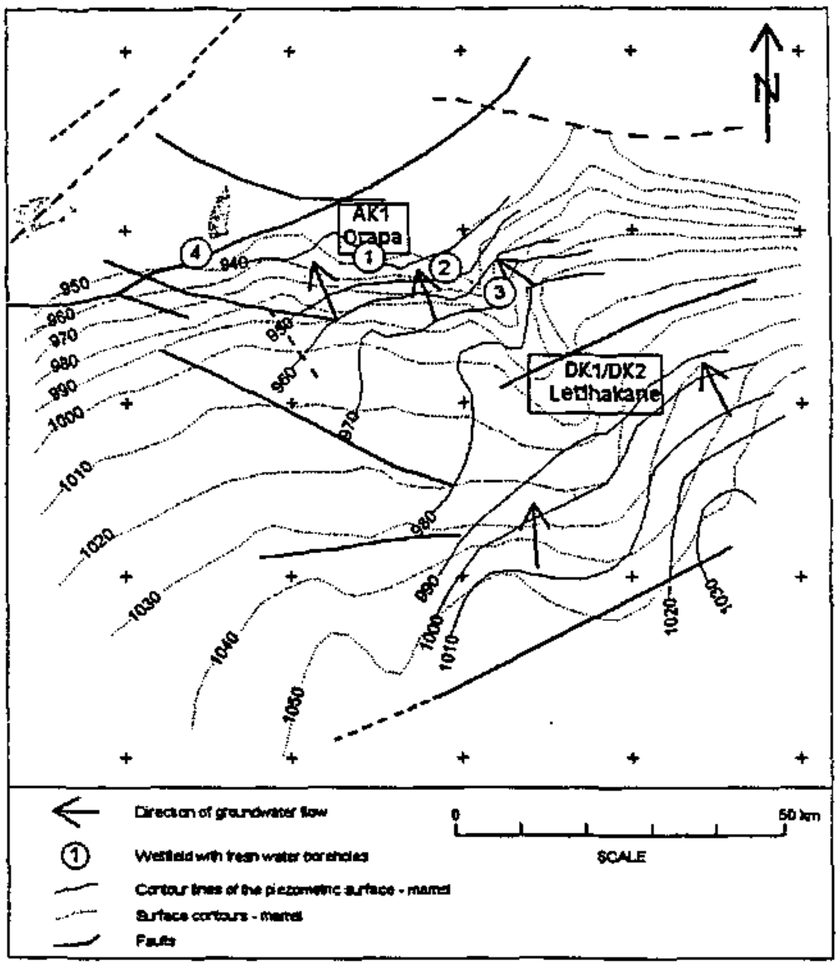

Fig. 1.2 General topography and piezometric levels in the area.

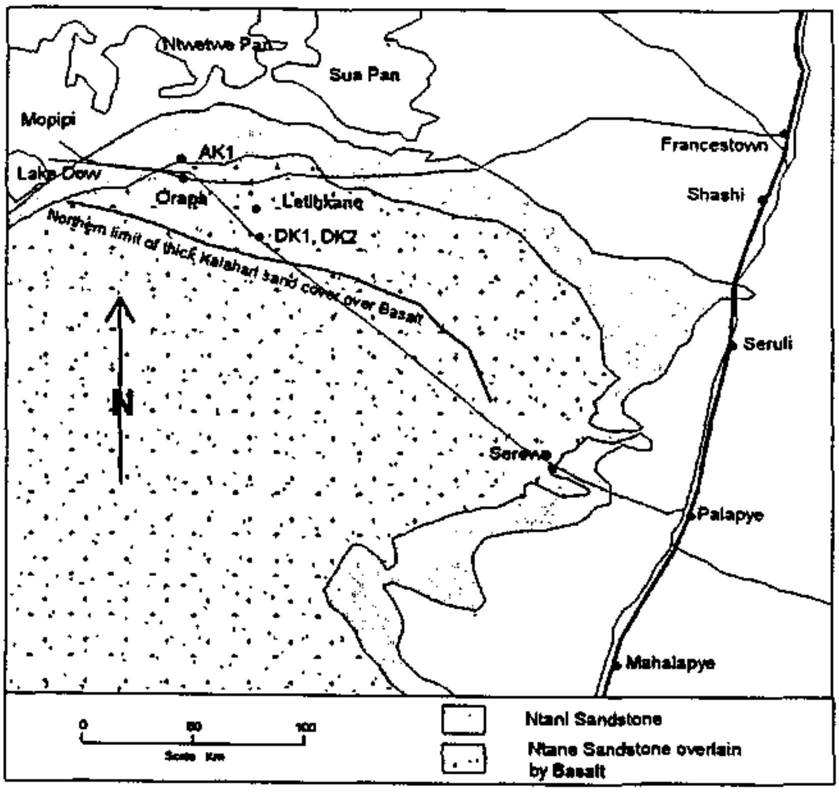

Fig. 2.1 Regional geology of the substrata in the Orapa/Letlhakane area.

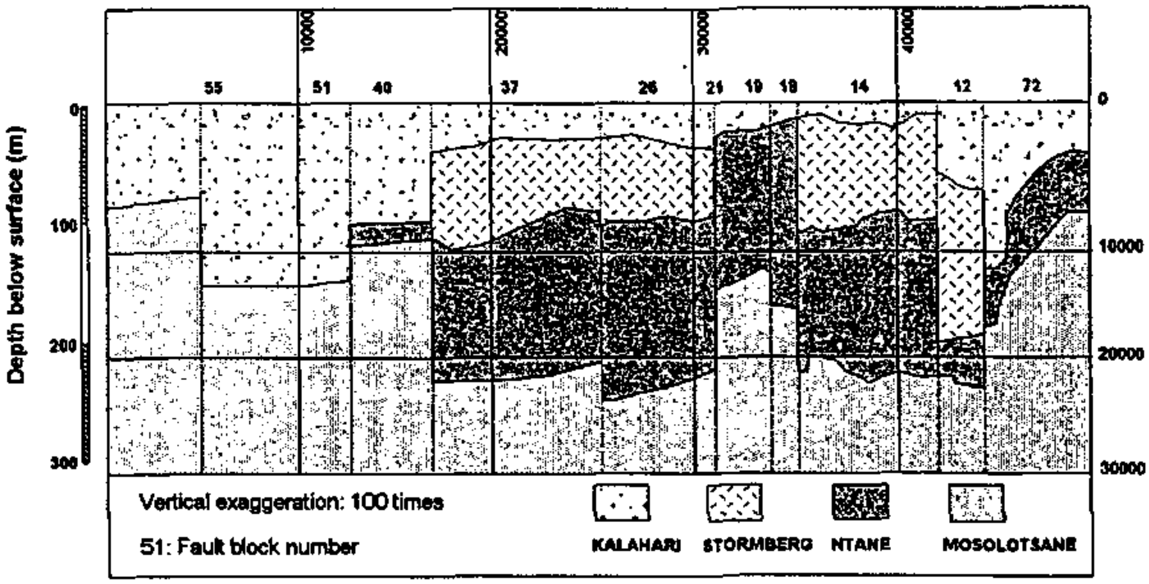

Fig. 2.2 Section showing the graben and horst structures resulting from block-faulting.

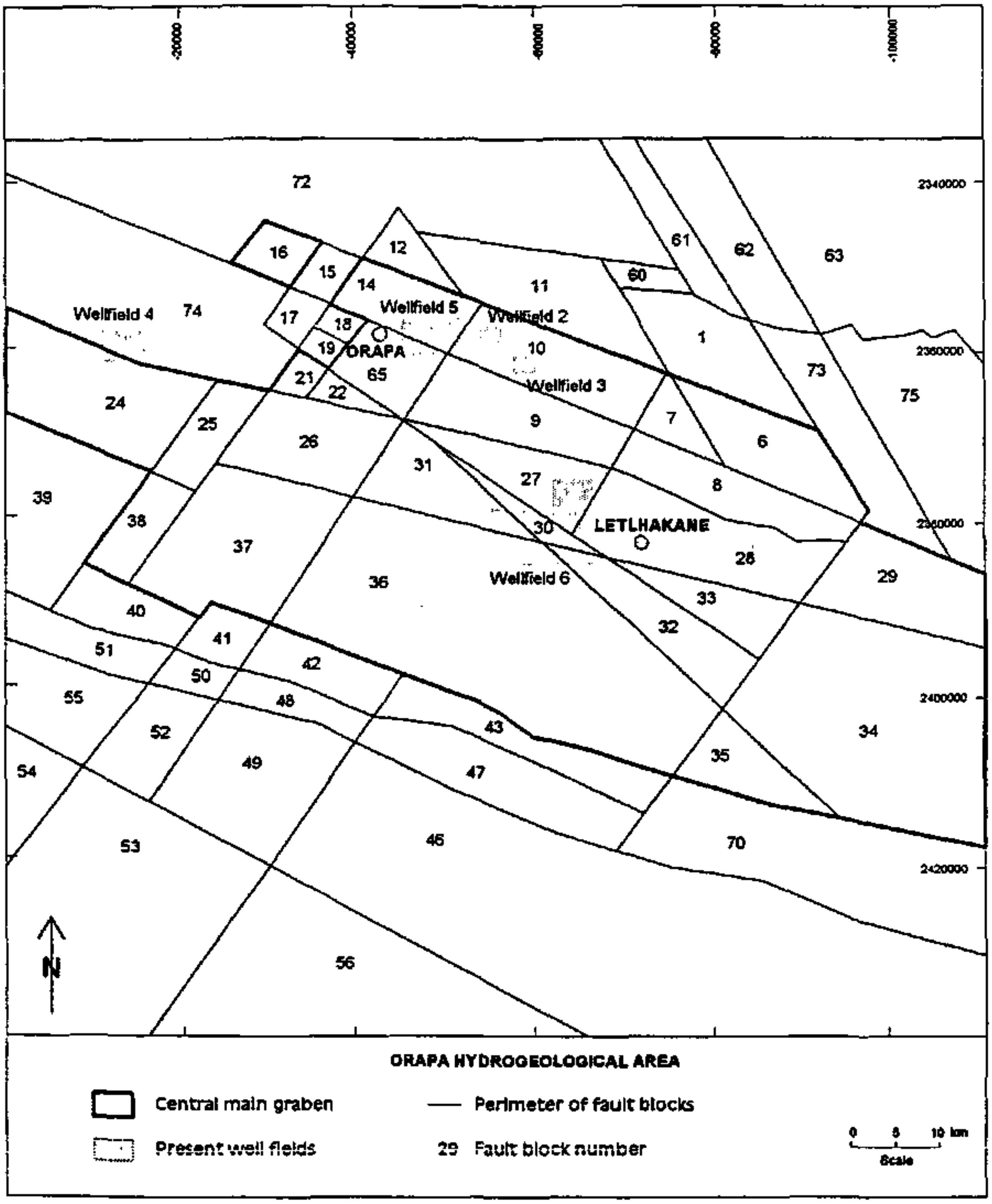

Fig. 2.3 Major structural deformations of the Ntane Sandstone Formation caused by block-faulting. The position of the main graben is indicated and the location of the different well-fields providing water for mining operations and domestic supply.

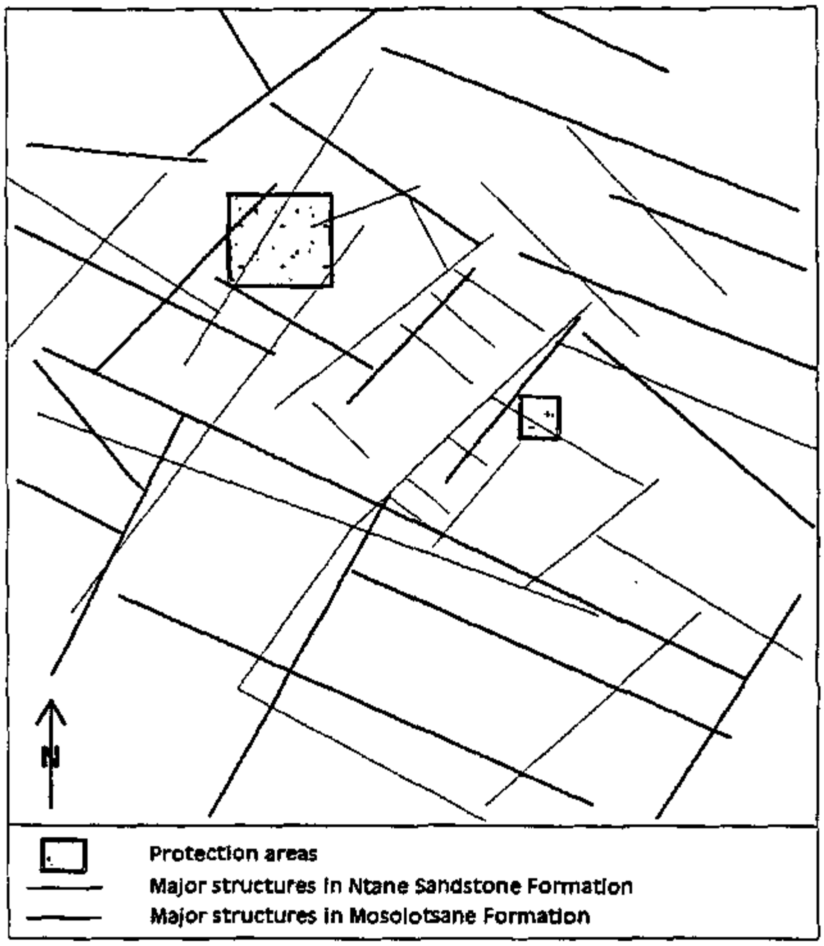

Fig. 2.4 Structural deformations of the Ntane Sandstone and of the underlying Mosolotsane Formation. The structures in the two formations does not seem to coincide.

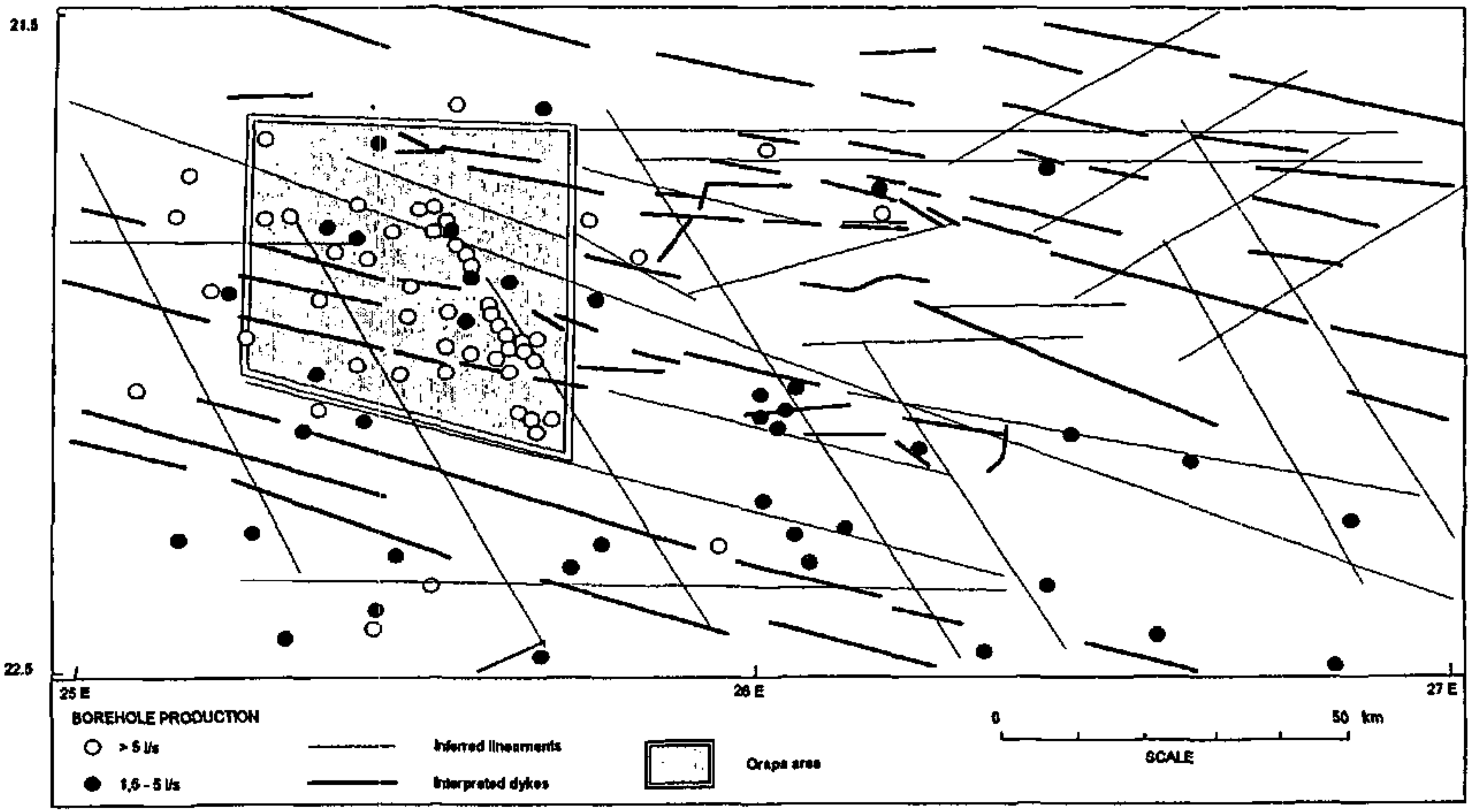

Fig. 3.1 Map showing the distribution of boreholes with relatively high yields in relation to the occurrence of dykes and lineaments which have been inferred from geophysical and remote sensing. The main concentration of boreholes are along the Letlhakane river.

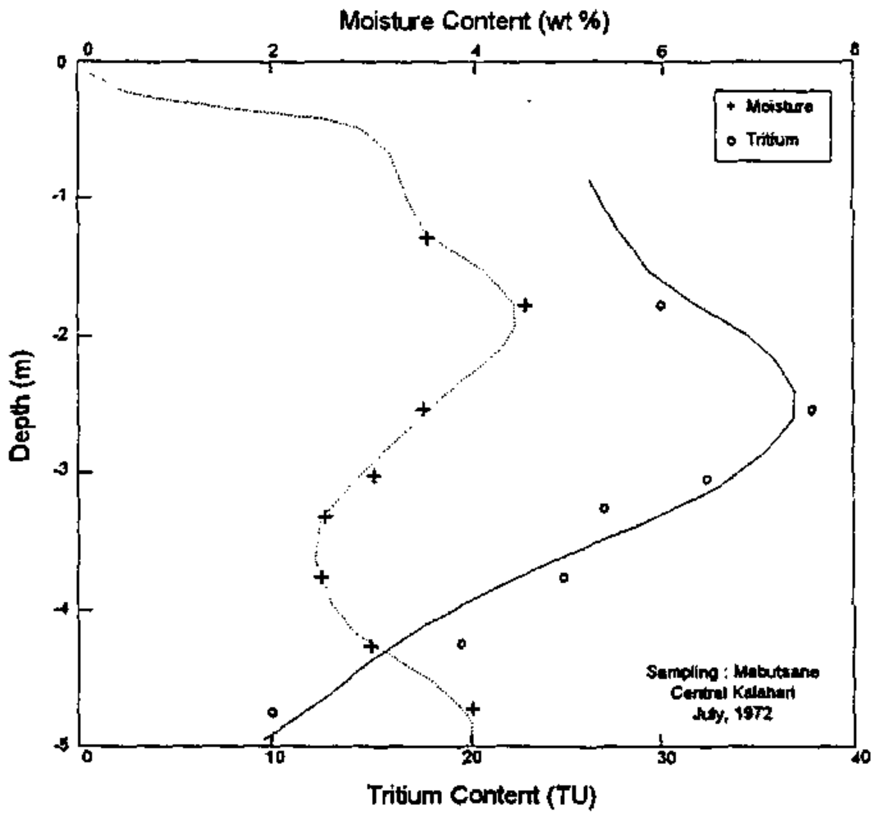

Fig. 4.1 Tritium profile and soil moisture with depth in Kalahari sand - after Jennings (1974) and Verhagen et al. (1974).

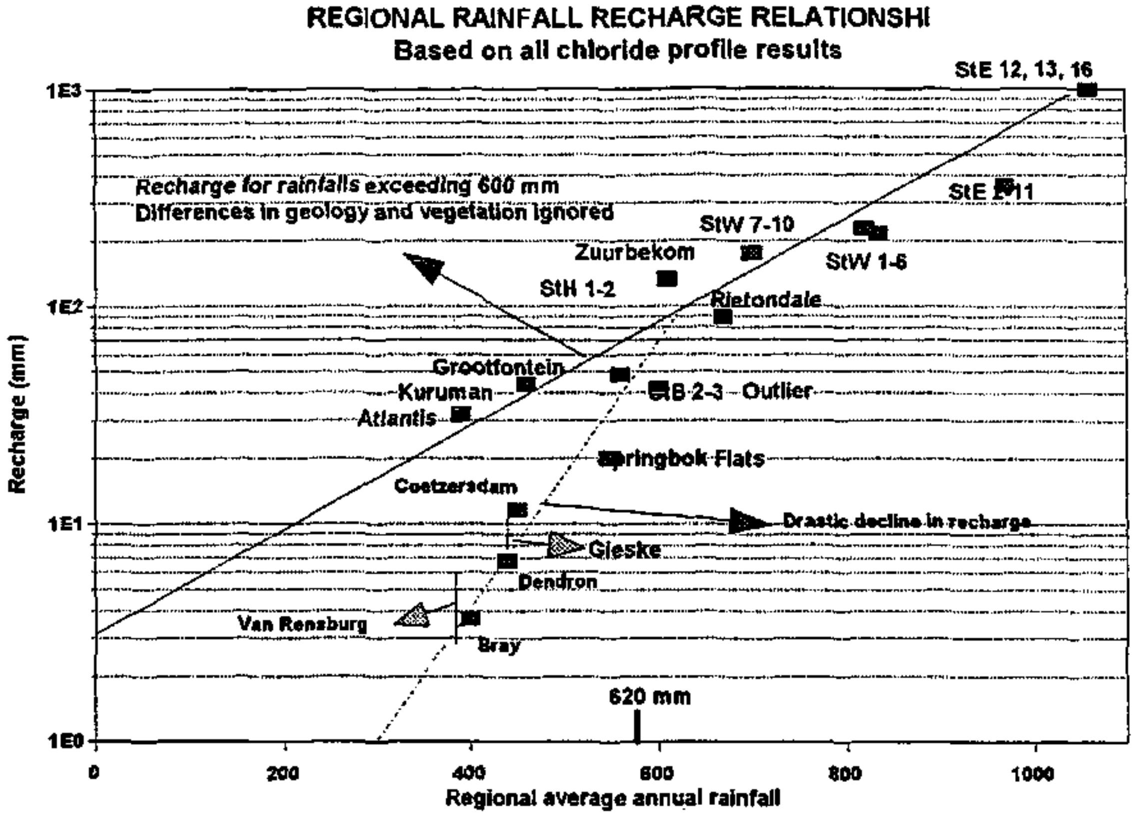

Fig. 4.2 Regional recharge for different areas in relation to the average rainfall, based on an analysis of natural chloride profiles in the unsaturated zone.

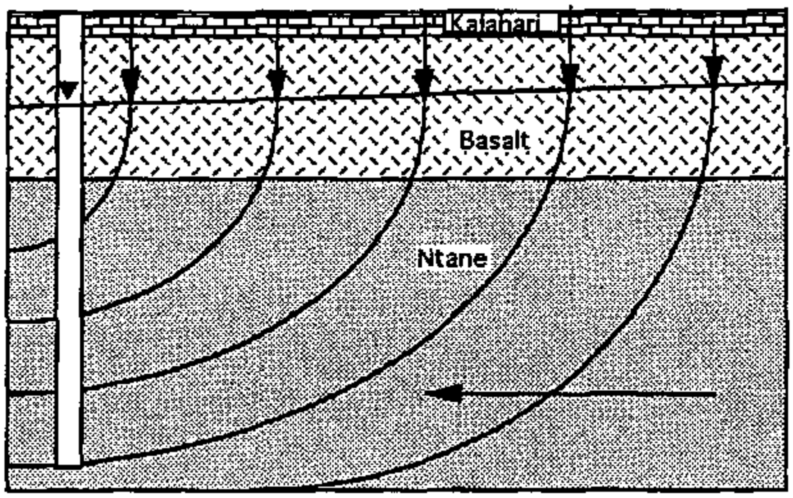

Fig. 4.3 (a) Diagrammatic representation of ground water age stratification in the Ntane under influence of ongoing, diffuse recharge and regional flow

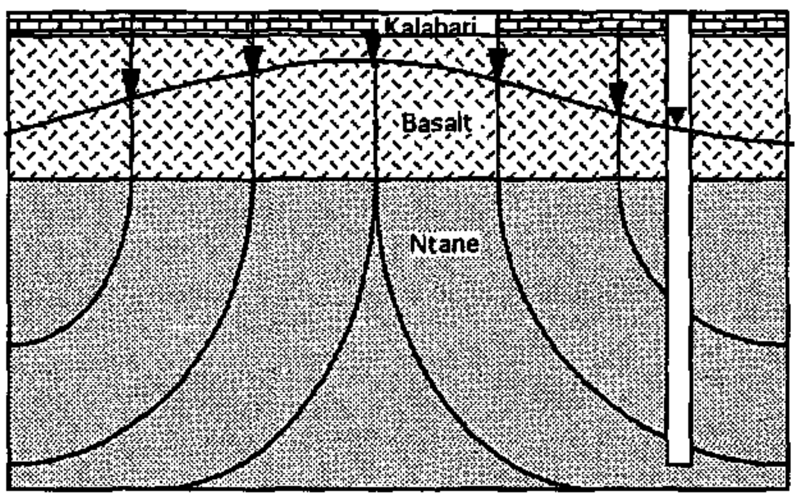

Fig. 4.3 (b) Diagrammatic representation of ground water age stratification in the Ntane under influence of localised recharge and mounding of piezometric surface

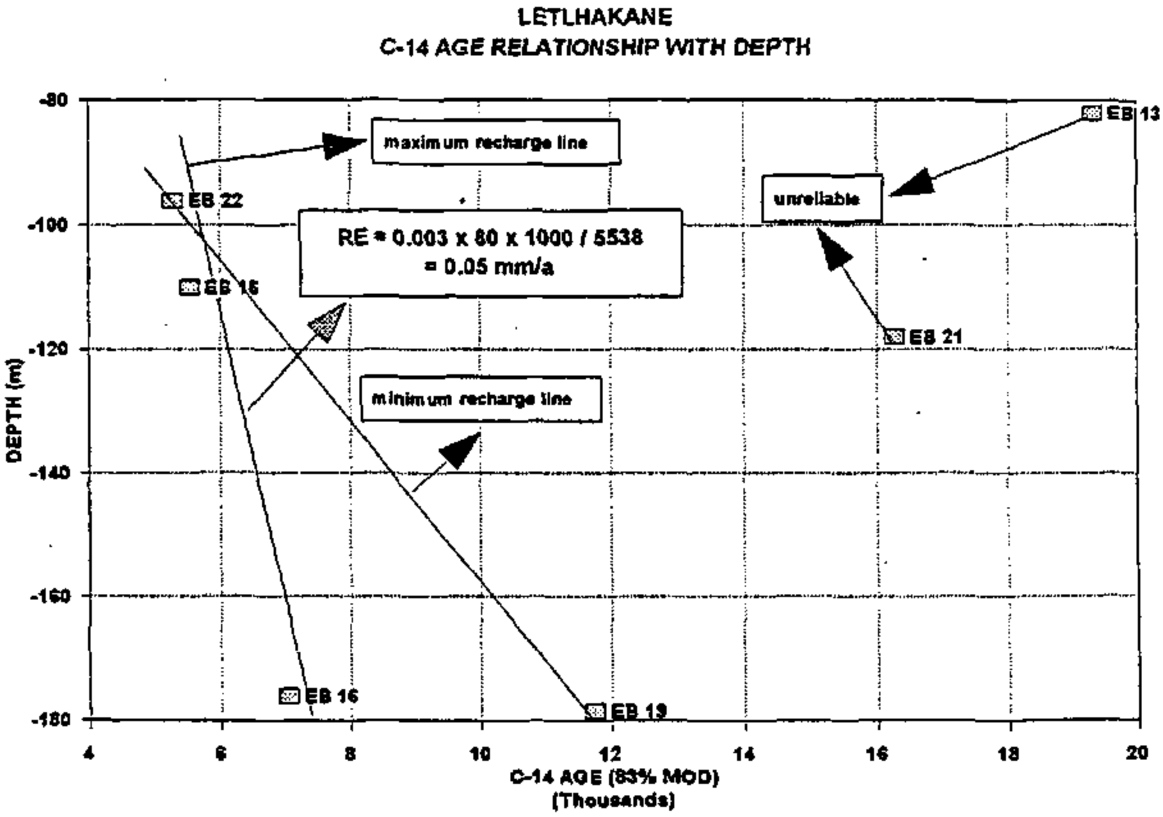

Fig. 4.4 Age relationship with depth based on samples obtained from the Orapa/Letlhakane area.

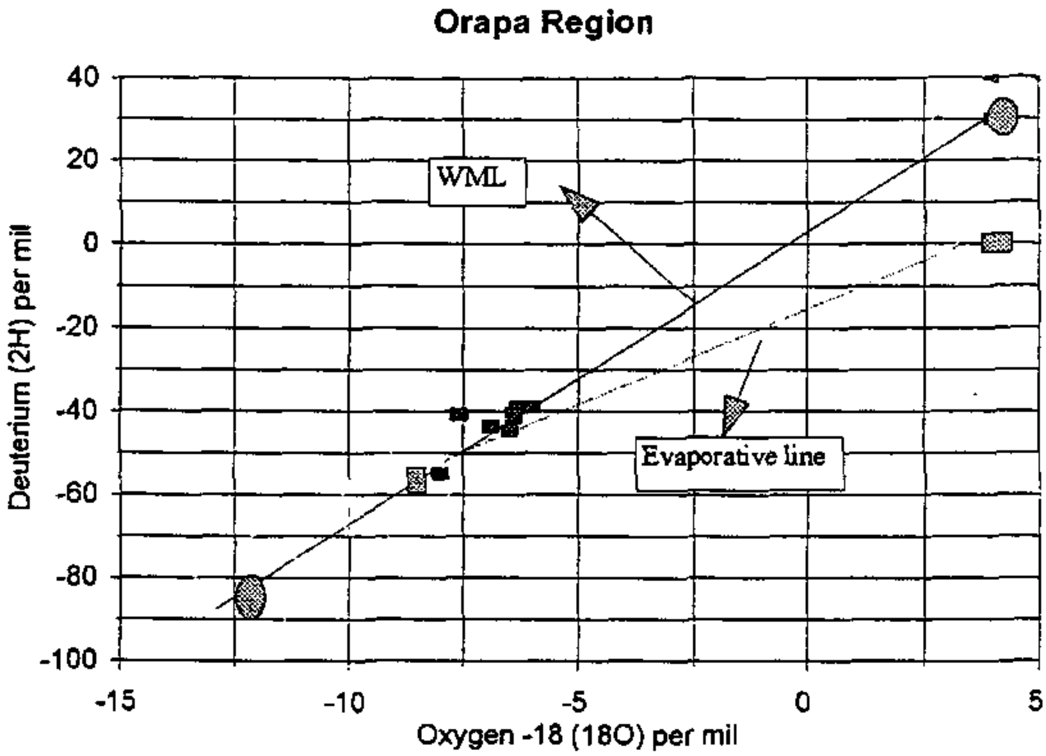

Fig. 4.5 Deuterium and oxygen-18 values of ground water in the Orapa/Letlhakane area in relation to the World Meteoric Water Line (WMWL)

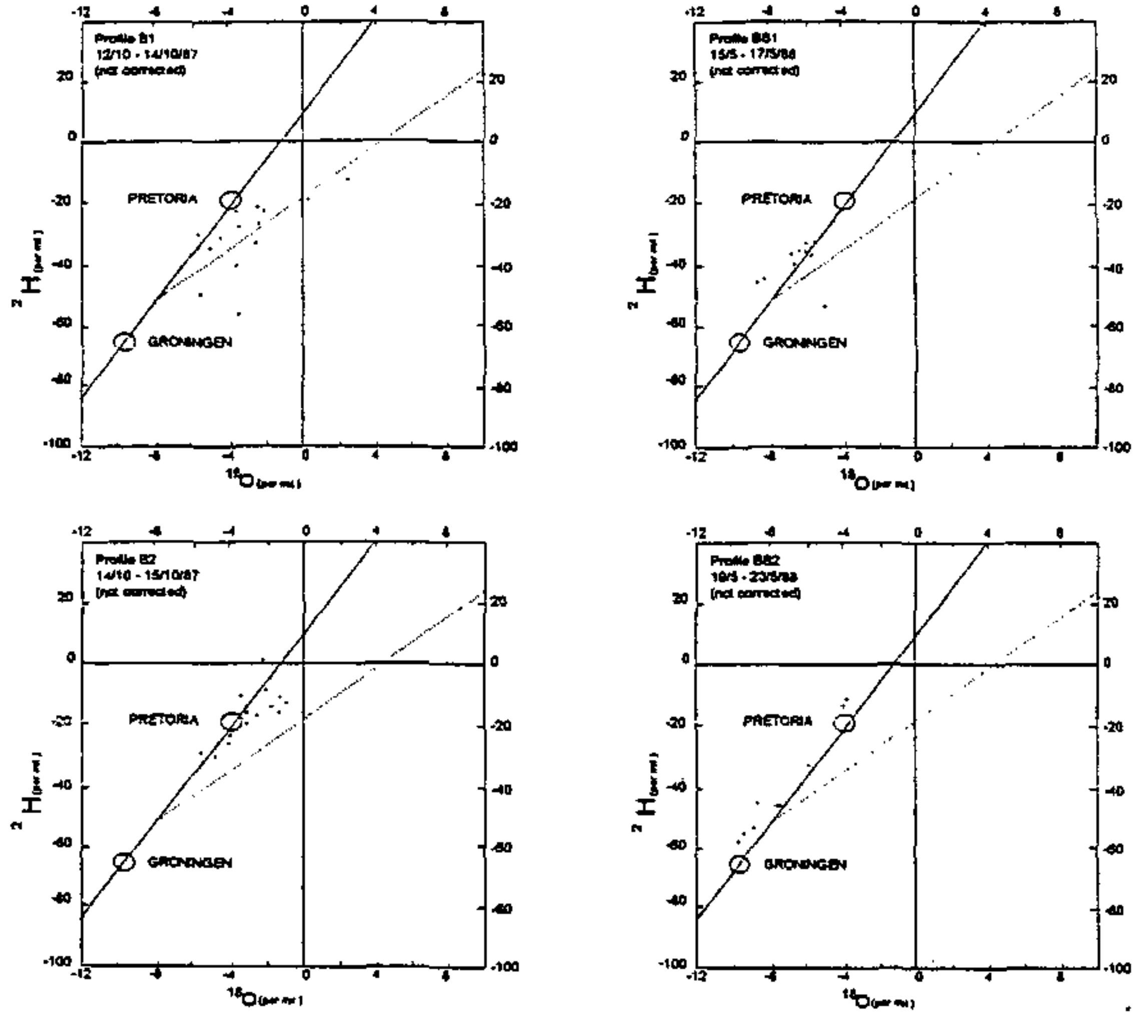

Fig. 4.6 Stable isotope concentrations in the unsaturated soil zone before and after the high rainfall of 1988 (after Gieske, 1992), - B1 and B2 prior to 1988, BB1 and BB2 after 1988.

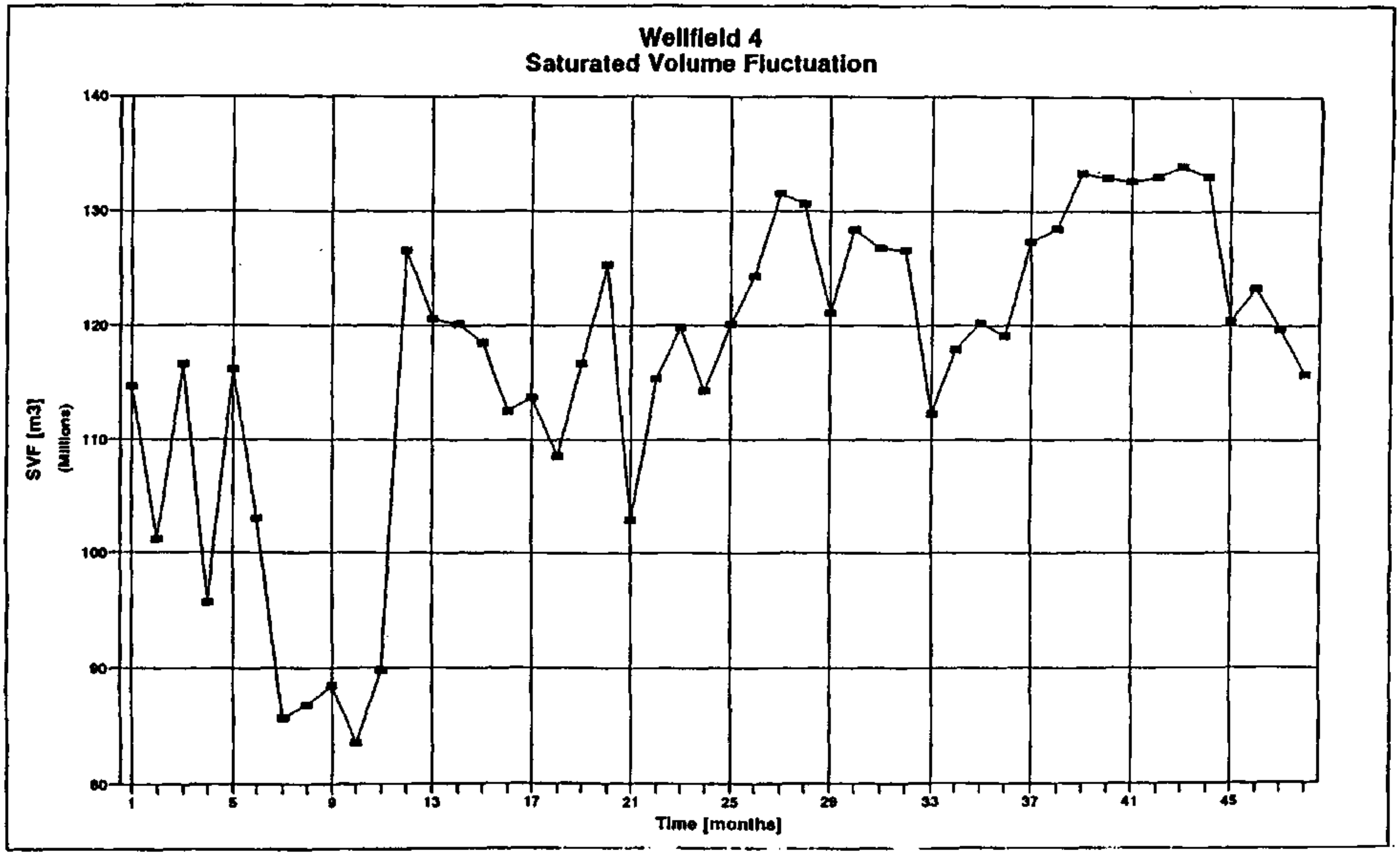

Fig. 5.1 Saturated volume fluctuations (SVF) for well-field No. 4 in the Orapa/Letlhakane area from which the recharge in relation to rainfall was derived.

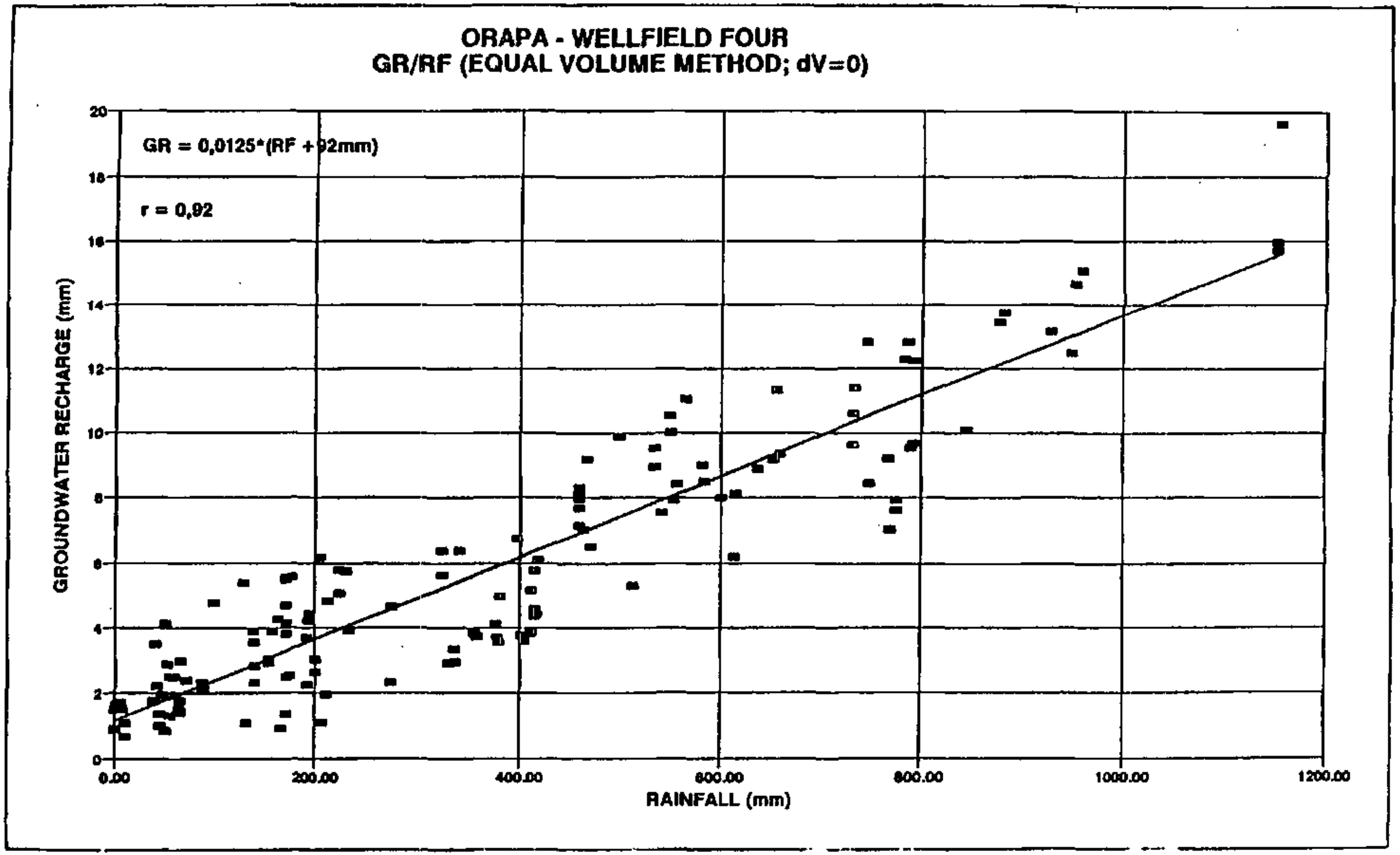

Fig. 5.2 Recharge estimated from the equal-volume techniques nd plotted in relation to the causative rainfall.

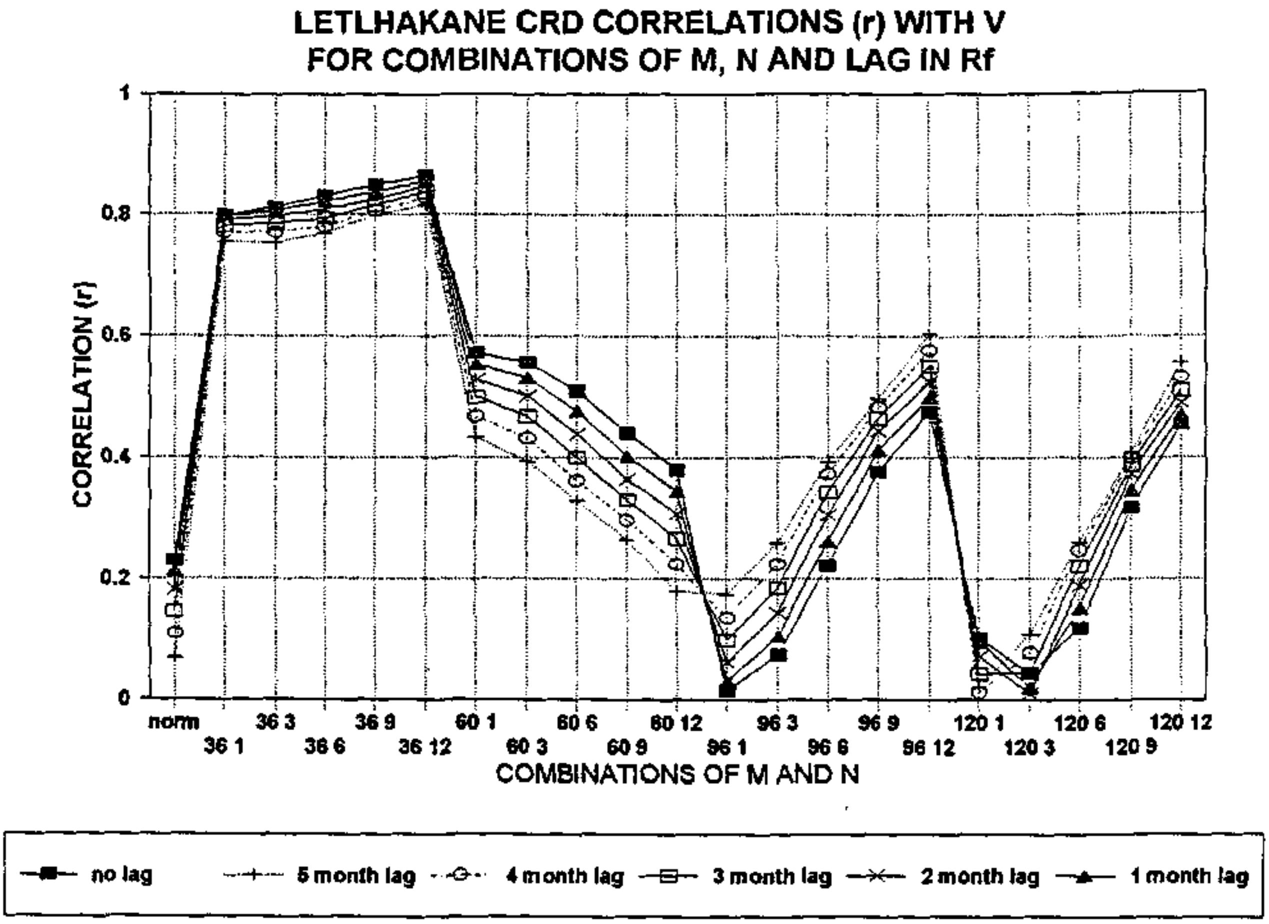

Fig. 6.1 Improvement in the correlation between the measured water-level response and the simulated response relating to the cumulative rainfall departures (CRD) where m indicates the short-term memory of the system and n the long-term memory. The effect of a lag between the short and the long memory is also shown but the best simulation is obtained with no lag and for m=12 months and n=36 months.

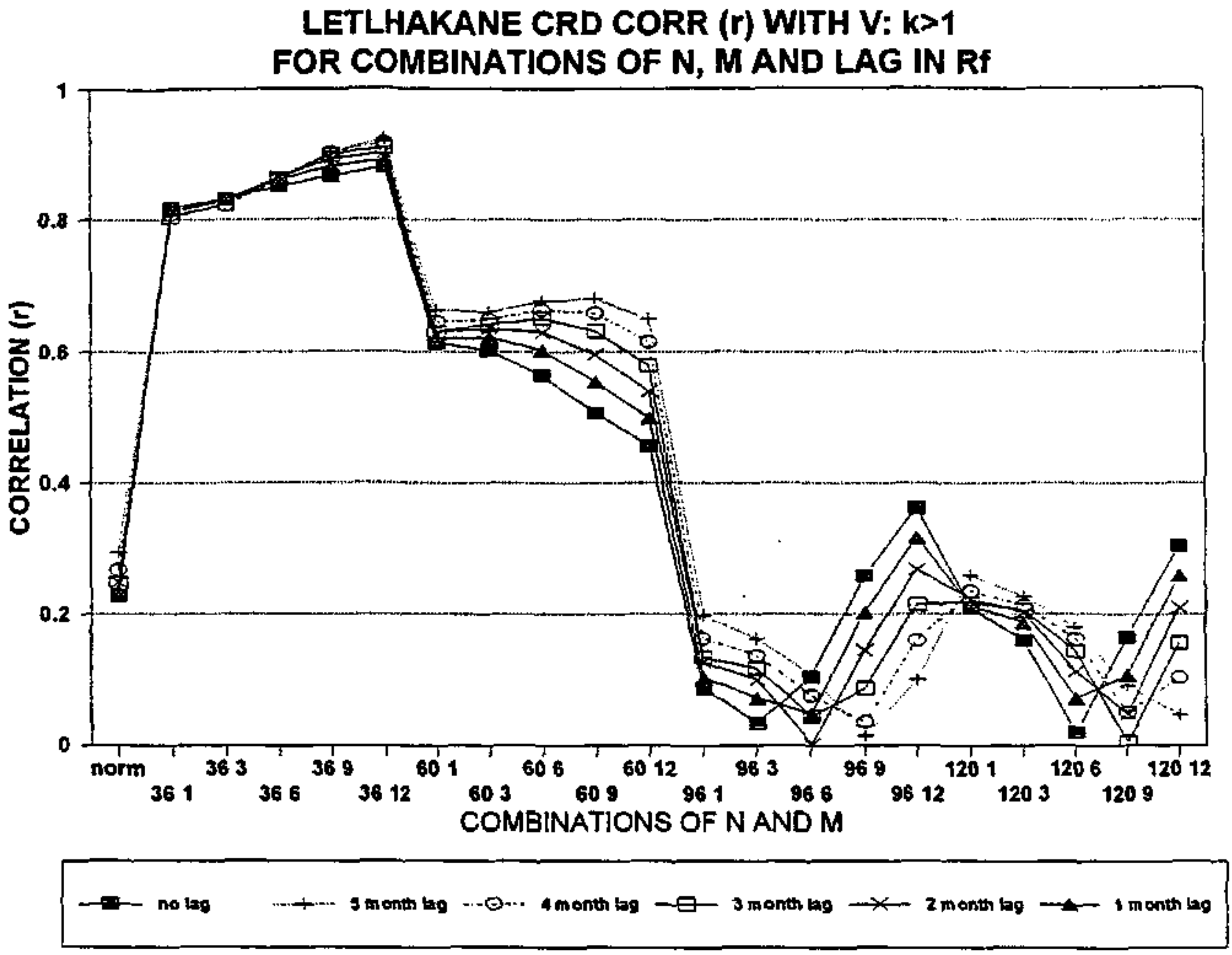

Fig. 6.2 Correspondence between the observed water-level response of the aquifer at well-field 6 and the simulated response derived from the CRD relationship indicating the improvement if the effect of abstraction is incorporated.

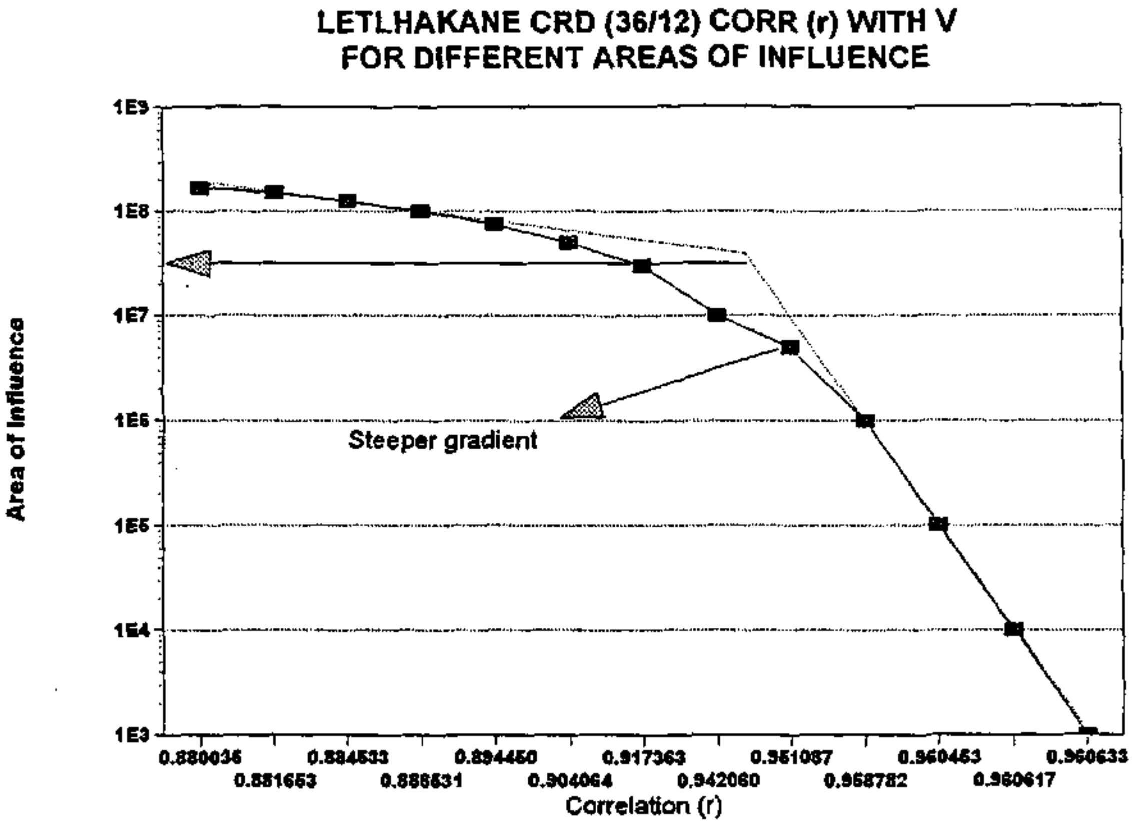

Fig. 6.3 Change in the correlation coefficient as the area of the aquifer is adjusted to obtain the areal size of the system which should best correspond to the observed water-level fluctuations. The correlation coefficient however continues improving as the area decreases, which indicate that the response is predominantly controlled by the abstraction and not by the area of the aquifer.

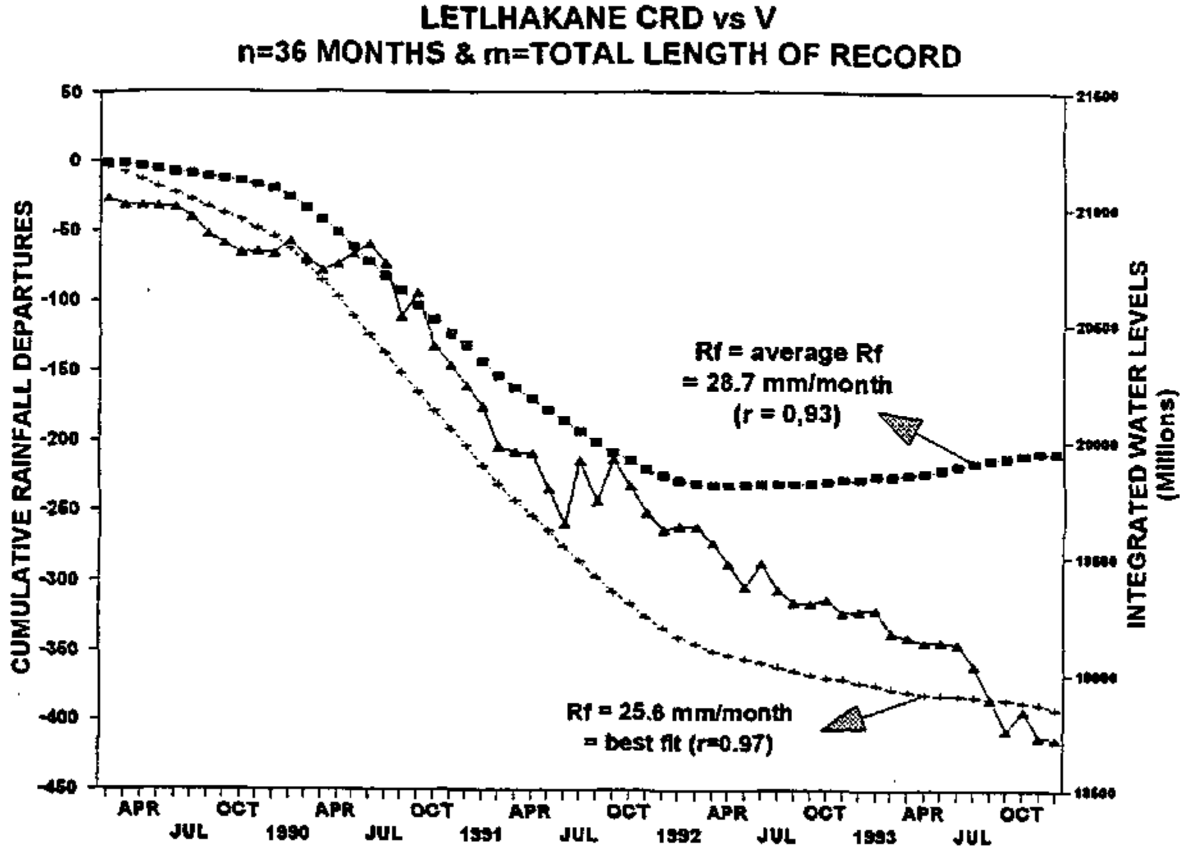

Fig. 6.4 Improved simulation obtained if the values of m > n in the CRD relationship. This implies that the recharge is related to the long-term average rainfall and the evaporative losses to a shorter period, with 36 months yielding the best correlation. A further improvement of the correlation is obtained if the effect of abstraction is incorporated as an equivalent ineffective rainfall.

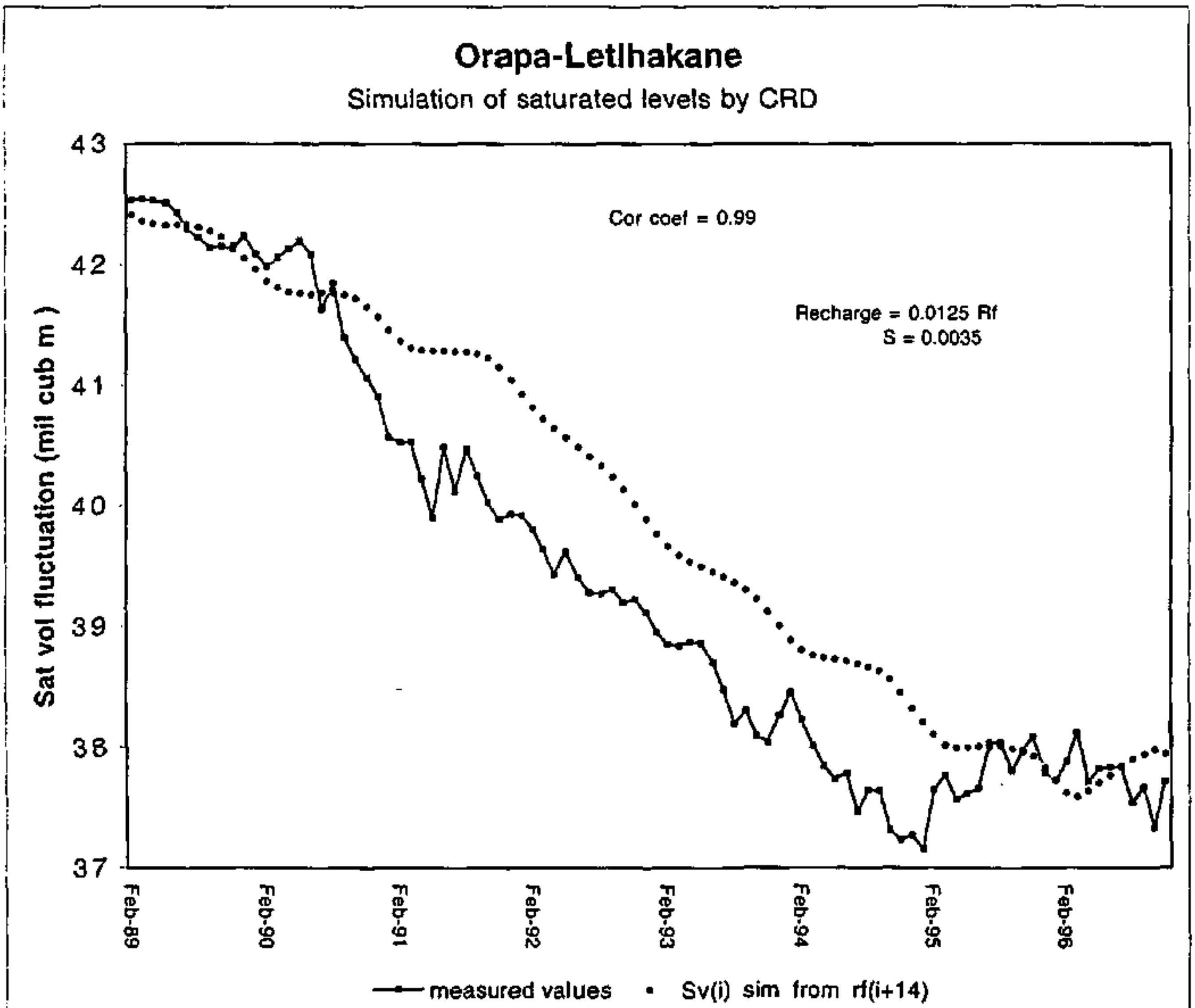

Fig. 6.5 Correspondence between measured values and those simulated by the Rf_{av} CRD series lagged by 14 months, incorporating monthly pumping.

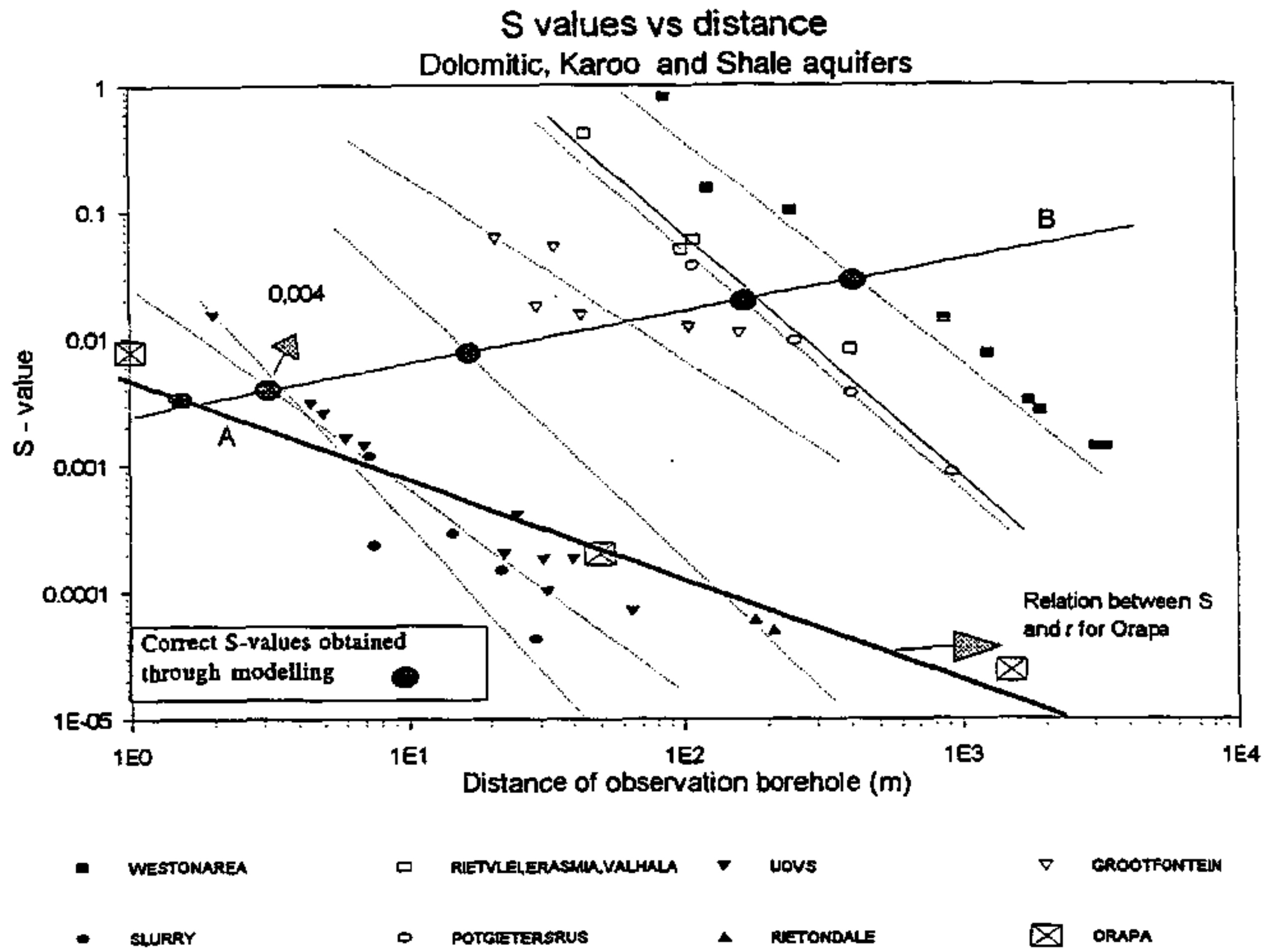

Fig. 7.1 Plot of the storativity values (S) against the distance of the respective observation boreholes from the abstraction point. The true S - value of the aquifer corresponds to the intersection of the line drawn through the points and the reference line which represents the true aquifer storativity.

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