USE OF NATURAL ISOTOPES AND GROUNDWATER QUALITY FOR IMPROVED ESTIMATION OF RECHARGE AND FLOW IN DOLOMITIC AQUIFERS

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Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

The dolomitic aquifers have been studied for many years and a variety of methods utilizing different techniques have been applied to improve estimates of the groundwater resource. The environmental isotopes ^{14}C and tritium, especially their introduction as part of the fall-out from nuclear tests in the recharge, has provided a unique opportunity to trace the propagation and reappearance of these tracers in the flow of especially dolomitic aquifers. The temporal fluctuations of these isotopes in various springs proved to be incompatible with hydrological evidence, indicating direct response of spring flows to high rainfall. For several springs, the tracer concentrations showed a much-diluted reappearance of the ^{14}C and tritium input pulse in the spring discharge. Failure to derive an acceptable model to simulate the inconsistent results has not only discredited the use of these environmental isotopes as a unique tool, but also groundwater scientists' understanding of the recharge and flow mechanisms in these and other aquifers.

Following a bi-modal input of the ^{14}C as part of the recharge and a two-box mixing model, successful simulation of the reappearance of the ^{14}C and tritium in the spring discharge has been achieved. The one box represents the shallow flow (recharge from more recent months) and the second the deeper flow from a period extending further back in time.

This reconciled most of the inconsistencies and not only provided new insights into the recharge characteristics and flow processes, but also a means to derive the mean residence time of water in the aquifer and from that the storage of groundwater in relation to the average recharge. Furthermore, the differences in the response of ^{14}C, tritium CFC and tritium as environmental tracers could be related to their uptake into the groundwater. The successful simulation of the recharge and flow in these aquifers also provided a means to assess pollution in these aquifers. A comparison of the ^{14}C model with a FEFLOW mass transport model has provided further verification of the conceptual basis of the ^{14}C model.

Objectives of the project (Virtually all of the objectives have been achieved)

To derive an acceptable hydrogeological model for simulating the reappearance of the ^{14}C pulse.

1. Developing and testing an *Excel-based simulation program* for ^{14}C that could be applied to dolomitic aquifers.
    - Improve the *estimation of groundwater recharge* and establish a model to simulate the flow and mixing of water in these systems.
    - Derive the *turn-over time and 'age' of water* in the dolomite aquifers and, from it, the ratio of the aquifer storage to the average annual recharge as well as the depth of the aquifer if the storativity (S_y) of the aquifer has been derived.
2. Checking and validating the basic premise of the ^{14}C conceptual model, i.e. that the recharge comprises a normal and direct component.
3. Using the ^{14}C model parameters to assess the reliability of tritium and CFC as tracers and to interpret their results according to the conceptual model.
4. Simulating the propagation of contaminants through a dolomitic aquifer according to the ^{14}C model and validate it by means of
    - a *simple model* of a section of the aquifer compiled in Excel software*;*
    - a *hydrodynamic model* of a section of the aquifer by means of a FEFLOW model.

5. Reliable simulation of the *natural variability of chemical elements* in groundwater (e.g. chloride, bicarbonate concentrations) and *assessment of pollution* in these aquifers.
6. Deriving a simple *regression relationship between the rainfall and recharge* that could be used as a general equation to obtain the variability of monthly recharge from rainfall.
7. Deriving the *depth of an aquifer and the storage* in relation to the average recharge from the turnover time of water in the aquifer.
8. Demonstrating that the ^{14}C, CFC and tritium modelling has made a *significant contribution* towards a better understanding of the flow of water in dolomitic aquifers, and *more effective utilization and better assessment of pollution* in these valuable groundwater resources.

The conceptual mixing and flow model

The relative mixing between the contributions of normal and direct recharge entering the saturated flow regime of the aquifer conforms to a two-box model in which

- the first box contains recent water that has been recharged in closer proximity to the spring and presents recharge that has occurred over a more recent period, in comparison to that of the second box that has been recharged from a much longer period preceding those of the first box;
- the ^{14}C content of the discharging water at the spring is controlled by the relative contributions from these two boxes, each representing the average concentration over two characteristic periods prior to a specific month.

It turned out that the simulated ^{14}C values had to be shifted in order to improve the overall fit of the model. This shift, ranging from a few months to several years, accounts for

- the delay before the recharge contained in the unsaturated zone reaches the flow regime of the saturated aquifer, and
- exchange of the incoming recharge with water contained in the aquifer matrix, which then becomes part of the dynamical flow.

The ^{14}C model has been applied to springs in the different areas and successfully derived the recharge and mixing periods.

Reliability of the recharge

A critical scrutiny of the recent *^{14}C simulation model* of the springs has indicated that *a reliable estimate of the average recharge is essential to yield the right recharge parameters*. The following proved to be the most reliable methods:

- o *The chloride mass balance method (CMB),* which provides the most independent method to derive the recharge on condition that the chloride concentration of the rainfall is reliable, which turned out not to be the case.

A new method has been used to derive more reliable estimates of the chloride of the rainfall. The recharge as derived from the flow records of a spring in relation to the recharge area, is converted according to the average rainfall to monthly recharge coefficients, which should be the same as those derived from the ratio of the chloride of the rainfall to that of the spring water. The value of the rainfall chloride is much lower than that obtained from the regional relationship by Bredenkamp et al. (1995), which has been based on available measurements of rainfall at the time. Similar estimations of the chloride of other springs have also yielded a lower input from the rainfall and have been corroborated by recent measured values.

- o Conversion of *spring flows to recharge.* This requires the area of recharge to be known, which could be derived from the delineated compartment boundaries and piezometric maps of the drainage.
- o The *Cumulative Rainfall Departure* (CRD) and the *Moving Average* (MA) methods that have provided a notable improvement in the estimation of the recharge. The latter method has provided reliable relationship between the recharge and the rainfall without incorporation of a threshold rainfall.

Establishing the bicarbonate as an alternative method to estimate recharge in other types of aquifers has not been addressed in the present project, as it turned out to be a major undertaking that would have to be covered in a subsequent investigation.

Summary of the main results

The research results of the ^{14}C simulations have provided validation of the conceptual model in producing an acceptable assessment of recharge controls, after it has been matched to revised estimates of the average recharge according to the CMB method. Thus the results of the ^{14}C simulations could effect better utilization, planning and management of the dolomitic groundwater resources.

Inserting these tracers into the corresponding ^{14}C model has assessed the reliability of tritium and CFC as environmental tracers. It turned out that an apparently larger dilution by the deep flow component is needed in the case of tritium than for the ^{14}C to obtain a best fit. The different response of the tritium can be explained by dilution of the tritium in the unsaturated zone where it is subject to exchange with a substantial reservoir of water molecules.

In the case of CFC a smaller multiple of deep flow is required than for the ^{14}C. This corroborates with the CFC input essentially occurring at the interface between the unsaturated and saturated aquifer, i.e. bypassing the unsaturated zone. The ^{14}C turns out to be the best tracer to obtain the residence time of groundwater in the saturated flow regime and the CFC being the next best, whereas the tritium would reveal the residence time including the unsaturated zone.

By applying an exponential decline of porosity with depth the turnover time of water in these aquifers were derived.

The significance of the project

1. The outcome of the project has significantly contributed to an improved understanding and assessment of the recharge and flow in dolomitic aquifers, i.e.
    - The successful simulations of the ^{14}C of the spring water has provided support to the bi-modal conceptual recharge model, in accordance with controlling parameters such as threshold rainfall and increased recharge for periods of higher rainfall;
    - A two-box mixing model applies in which the one box represents the shallow (more recent recharge) and the second the deeper flow from a period extending further back in time.
2. The ^{14}C model has revealed the local and regional differences between the recharge controls of the various aquifers, which seem to be in agreement with their hydrogeological characteristics, e.g. the thickness of unconsolidated-cover of soil, rock outcrop or calcrete. Anomalously low ^{14}C values could be attributed to recharge from a non-dolomitic source, e.g. bordering quartzite aquifers.

3. The impact of the unsaturated zone overlying the dolomite aquifer is manifested in the simulation model as part of the overall delay of the ^{14}C pulse. Delay is also caused by water contributed from the aquifer matrix. The ^{14}C model revealed that water contained in the aquifer matrix actively participates in the transmission of flow through the aquifer.
4. The turnover time of water in the aquifer has been derived from the ^{14}C model and comprises two components, i.e.
   - Water in the unsaturated zone of which contribution to the saturated flow-regime is lagged;
   - Water flowing through the saturated porous aquifer.

   The turnover time of the latter component has been used to obtain the ratio of groundwater in storage to the average annual recharge, which provides a valuable contribution to assessment of the exploitation potential of these aquifers after provision for the reserve has been made.
5. The propagation of pollution in dolomite aquifers has successfully been demonstrated for the Turffontein spring by inverse modelling to establish the input that has been responsible for the contamination. From this the prolonged impact of the pollution of the aquifer for different decontamination options could be illustrated.
6. Inserting tritium and CFC as input into the ^{14}C model has proved that they could also be used as environmental tracers, and that the tritium model incorporates the influence of the unsaturated zone, and CFC only that of the saturated aquifer. The ^{14}C model incorporates part of the unsaturated zone and all of the saturated aquifer and appears to be the most reliable isotope to use, also in view of the fact that no correction for radioactive decay is required, which has to be incorporated in the tritium simulations.
7. A simple rainfall-recharge formula has been derived from the outcome of the ^{14}C simulations and of the flow the springs. This produced a binomial equation that conforms to the MA method without having to incorporate the threshold rainfalls.
8. A relationship between the recharge and bicarbonate concentrations of dolomitic aquifers has been derived in relation to the average annual recharge coefficients, which have been determined from the chloride concentrations of the spring water according to the CMB method.
9. The project will significantly contribute towards implementing a management policy and planning strategies on groundwater utilization that are based on sound hydrological principles. A follow-up project is essential to implement the results into the policy-making and effective strategies of the local management of aquifers. This would include reviewing the associated monitoring that would be required for improved assessment of the resources, and provide more effective management and the implementation of consistent scientific-based policies. The results that have been obtained from the project could be fruitfully applied to many countries with similar aquifers for a range of climatic conditions.
10. The outcome of the project would make a direct contribution to capacity building of the full spectrum of water managers, planners and those utilizing the resource, insofar as having provided a much clearer understanding and validation of the hydrological rationale that governs the occurrence and estimation of groundwater resources. The results from the project also provide essential links towards the provision of a blueprint for policy-making and effective practical management of the groundwater resources of South Africa and elsewhere in the world.

DEFINITION/EXPLANATIONS OF TERMS, ABBREVIATIONS AND ACRONYMS

^{14}C: The radioactive isotope of carbon that is being produced in the atmosphere and which is introduced into the groundwater by the dissolution of carbonate by recharging rainfall. Although usually used as a dating tool, the increases of ^{14}C from the fall-out of thermonuclear tests is applied as a tracer and time-reference in this study.

Age of the water (years): The average age for the water in the aquifer, which is the total residence time, i.e. the turnover time in the saturated aquifer plus the lag due to water stored in the unsaturated zone as well as interaction with the water contained in the aquifer matrix.

Bi-modal recharge: Postulated dual recharge that occurs if a lower and higher threshold rainfall is exceeded giving rise to different ^{14}C input values into the aquifer.

Calcrete: The deposition of carbonates that has been precipitated from an oversaturated solution of bicarbonate in the groundwater.

CFC: Highly stable chlorofluorocarbon gases being used in the refrigeration industry.

(CFC11, CFC12 and CFC13): These CFC molecules have been released into the atmosphere in accumulating concentrations, which have entered the groundwater and are being used as a method to date the groundwater.

Cl_{gw}: The chloride concentration of the spring water.

Cl_{Rf}: The average chloride concentration of the rainfall, which is critical for reliable estimation of the groundwater recharge according to the CMB method.

CMB: The chloride mass balance method based on the ratio of the concentration of chloride in the rainfall to that of the groundwater. This provides a reliable estimate of the recharge coefficient of groundwater in the dolomitic aquifers if the chloride of the rainfall is reliably known.

Cumulative Rainfall Departure (CRD): The sum of the departures of monthly rainfall from the long-term average rainfall to mimic the groundwater level response.

Cut-off rainfall: Synonymous to the threshold rainfall that has to be exceeded to effect recharge.

Dry chloride input: The contribution of chloride from dust that is precipitated in the rain gauges.

Effective pumping area: Effective areas, which best simulate the groundwater level fluctuations that is derived by the CRD or MA method.

Environment Isotope Group (EIG): Previously the Isotope Laboratories of the Schonland Institute of the Witwatersrand University.

CSIR Quadru: The Quaternary Dating Research Unit at the CSIR responsible for dating and isotope analysis.

Equal volume method (EVM): Deriving the groundwater recharge from the total abstraction or flow of a spring during periods representing recurrent equal-status of water levels or flows. This circumvents having to know the storativity (S_y) of the aquifer.

$Error_{av}$: The sum of the differences squared, i.e. between the simulated and measured ^{14}C values to obtain the best least-square fit between the simulated and measured values.

Excel model (Xu): An analytical model (programmed in Visual Basic) to simulate the reappearance of the ^{14}C pulse in the spring flow.

Model parameters (^{14}C): The parameters that have been adjusted in the ^{14}C *model* to obtain the best simulation as shown in the following example:

^{14}C simulation: Grootfontein Molopo

Factors **Error**	**28.96**	**Minimized error for the best simulation**
Lower threshold (mm)	38.2	Low threshold rainfall for normal recharge component
Higher threshold (mm)	68.2	Threshold rainfall for direct recharge component
Recharge factor (N)	0.123	Recharge coefficient for normal recharge via the unsaturated zone
Recharge factor (D)	0.078	Recharge coefficient for direct recharge component
^{14}C factor (N)	0.85	Fraction of incoming ^{14}C applied to the normal recharge
^{14}C factor (D)	0.552	Fraction of recharge for the direct recharge component
Multiples of deep flow	4.03	Contribution of deep-flow as multiples of the shallow component
Calculating ^{14}C of spring water		
Lag period 1 (months)	36	Period representing the shallow flow component
Lag period 2 (months)	338	Period representing the deep flow component
Long term average rainfall		Details of the input-rainfall series
Start year	1922	
Start month	1	
Total months for long term average rainfall	937	
No. of months included in averages of:		
Weighting factor of the recharge coefficient	24	Weighting factor to vary the effective recharge coefficient
^{14}C of the normal recharge component	36	Averaging period for normal recharge component
^{14}C of the direct recharge component	36	Averaging period for direct recharge component
Final lag period (months)	57	Lag in ^{14}C response due to recharge contained in the unsaturated zone and admixture of water released from the aquifer matrix
Simulated HCO_3 of spring (mg/l)	220.53	Simulated bicarbonate concentration of spring water
Measured HCO_3 (mg/l)	228	
Chloride recharge coefficient	0.0892	Average recharge derived from the CMB method
^{14}C model recharge coefficient	0.0892	Average recharge derived from the ^{14}C simulation

Final lag-period: The lag in ^{14}C response due to recharge contained in the unsaturated zone and by admixture of water in the aquifer matrix.

Inverse modelling: Deriving the input, e.g. of a contaminant tracer from the observed output response.

Karst: The dolomite having been transformed into an excellent aquifer by the dissolution of carbonate by the rainfall.

MODFLOW: A commercial hydrodynamic model to simulate the flow and transport of contaminants in an aquifer.

Moving Average method (MA): Relating the response of groundwater levels and recharge to the moving rainfall over a preceding period.

R_{av}: The average recharge, e.g. derived from the flow measurements of the spring.

Rf_{av}: The average rainfall for the corresponding period for which chloride measurements have been obtained.

Storativity: The capacity of an aquifer to store water, representing a combination of water stored in pores (Specific yield Sy), in fractures (S_f) and of the aquifer matrix (Sm). For a phreatic aquifer the storativity represents the specific yield (S_y), which is the volume of water per unit volume of aquifer. For confined aquifers the storativity represents the response of the water level to a change in the hydrostatic pressure at depth and not from dewatering of the aquifer.

$t_{1/2}$: The half-life of a radioactive isotope, representing the time for the initial concentration to decay to 50 %, e.g. 5730 years in the case of ^{14}C and 12.3 years for tritium.

Tritium (^{3}H): Radioactive hydrogen atom that is produced naturally by cosmic ray interaction with nitrogen atoms in the atmosphere. The introduction of tritium from the fall-out of thermonuclear tests has injected a pulse of high tritium, which could be used to trace the recharge and flow of water in groundwater aquifers similar to ^{14}C.

TU: The tritium unit used to express the low concentrations of tritium. 1 TU representing one tritium atom in 10^{18} atoms of hydrogen.

Turnover time (yrs): The period over which the water in the aquifer is replaced. This also represents the volume of water stored in the aquifer as multiples of the average annual recharge.

Weighting factor: The factor to vary the recharge coefficients proportional to the ratio of the rainfall over a short period relative to the long-term average precipitation.

Wet chloride: The input of chloride only from the rain excluding dry deposition of chloride during rainless periods.

Section 1. Introduction

1.1 Background to the Study

Dolomitic aquifers are probably the most productive aquifer systems in the RSA and constitute the primary or supplementary water supply of various urban centres, irrigation and rural areas (see Table 1) , e.g. Gauteng (City of Tshwane, Zuurbekom, Khutsong), Mpumalanga (Delmas, Nelspruit), NW Region (Lichtenburg, Mafikeng, Itsoseng, Ventersdorp) and the Northern Cape (Vryburg, Kuruman and Sishen) and many more rural communities. Dolomitic groundwater is also extensively used for irrigation in the Schoonspruit area, the Mooi River catchment, Babsfontein, Tarlton area, East Rand, Sabie and Graskop areas.

Table 1. Some quantitative data on the utilization of groundwater of some of the dolomitic aquifers.

Dolomitic Areas	Abstraction ($m^3.10^6$ /a)	Comments/Purpose and Reference
NW province		
• Itsoseng/Lichtenburg	37.3	Irrigation and domestic use. Bredenkamp (2004)
• Mafikeng Grootfontein	38	Irrigation and water supply. Veltman (2003)
• Schoonsprui t/Grootpan • Zeerust	40.9	Irrigation and water supply to Zeerust and Dinokana/Lehurutse. (Hubert et al., 2004)
Northern Cape	3.5	Water supply to 230 000 people, i.e. 39 % of total population of the area. (Van Dyk and Peters, 2005)

In the gold-mining regions (e.g. upstream of Gerrit Minnebron in Figure 1), the dolomite aquifers are vulnerable to pollution from the mining effluents, e.g. sulphate and radioactive products. The dolomite aquifers present a major risk of flooding of the gold mines in the West Rand, but also provide a useful source of water as a by-product, e.g. to the semi-arid region of the Sishen iron-ore mine.

The dolomitic aquifers of South Africa shown in Figure 1 have been studied for many years (Enslin, 1970; Fleisher, 1981; Foster, 1987; Vegter and Foster, 1990; Bredenkamp et al., 1991; SRK, 1986; Kok, 1986; Smit, 1980, 1995). The characteristics and diversity of the hydrogeology of these aquifers are sufficiently covered in the cited references and has not been repeated in the present project. A main feature of the South African dolomites is that they are subdivided into smaller compartments by thin vertical dyke intrusions, which act as barriers to the lateral drainage of groundwater. This gives rise to the occurrence of springs at the topographical lowest point where these dykes force the groundwater to overflow as springs.

A variety of methods utilizing different techniques have been applied to improve estimates of the groundwater resource (refer Section 2). Quantifying the recharge and storativity of the aquifer has proved to be difficult, in view of the complexity of the dolomitic aquifer and its karstification through the dissolution of the carbonates by the mild-acidic rainwater recharge. The water-bearing features and the recharge of the dolomite are intimately related to the tectonic deformation of the dolomite caused by uplifting and structural impacts, such as a high incidence of intrusions of diabase dykes and quartz veins with occasional smaller en-echelon dislocations and a few major faults (ref. Veltman, 2003; Wiegmans, 2004).

Simulating the reappearance of the ^{14}C and tritium in the spring discharge from which to derive some of the recharge and flow characteristics of the dolomitic aquifers, is one of the main objectives of the present project (see Section 1.2). Furthermore a comparison of the response of CFC as environmental tracers is also carried out.

The new approach presented in this paper conforms to the lumped parameter approach (Maloszewski and Zuber (1996) insofar that the spatial recharge is the same but varies for each month according to the rainfall being higher than two threshold values, thereby determining the bicarbonate concentration of the two components of infiltrating groundwater with different ^{14}C values, although they both represent the recharge of that month. For each month's recharge the average ^{14}C concentration of the mix of the two components is calculated with incorporation of the amounts of recharge that has occurred. Correspondence between the chloride and bicarbonate concentration of the spring water with the simulated average values provided verification of the reliability of the bi-modal recharge concept. The simulation of the tracer responses of the springs also provided a lumped and integrated response of the spatial and temporal variations of recharge of the area that sustain the spring flow. With regard to the complex mixing that occur in dolomitic aquifers that could comprise of matrix porosity, fracture porosity and dissolution channels (c.f. Maloszewski and Zuber 1982) the specific yield is encompassed in the present model as a bulk average value.

The full series of average ^{14}C input of each month is then mixed according to two periods representing two boxes to derive the ^{14}C content of the spring discharge of each month. The mixing of the two boxes also complies to a lumped model, the one representing the average ^{14}C of the recharge over a shorter period preceding a specific month (more recent water), and the second the average ^{14}C over a longer period prior to the first (representing the deeper flow that admixes with that of the first period). The relative contributions of recharge from the latter period with that of the first period determine the concentration of the ^{14}C of the spring discharge of a specific month, which is checked against the measured values. Thus, contrary to the usual exponential modelling, mixing in this model occurs over a fixed (finite) moving period for each aquifer, and accordingly the time-varying ^{14}C pulse is thus used as a classical tracer to simulate the observed series of ^{14}C at the spring (see Section 4).

1.2 Objectives of the project

The present project has been initiated with support from the Water Research Commission and is an extension of a successful simulation of ^{14}C of a few springs by Bredenkamp en Van Wyk (2005) that has been critically examined by Vogel and Bredenkamp (2005 – submitted for publication in the Journal of Hydrogeology). The objectives of the present study has been rephrased more specifically:

- To derive an acceptable hydrogeological model for simulating the ^{14}C pulse that has been introduced by thermonuclear testing via rainfall-recharge into the dolomitic aquifers and its reappearance in the spring discharge.
- To establish and test an Excel-based simulation program for ^{14}C that could be applied to dolomitic aquifers by which to

- improve the estimation of groundwater recharge and establish a flow model to simulate the flow of water through these systems;
- obtain the recharge coefficients and threshold rainfalls above which recharge in the different dolomitic aquifers occurs;
- derive the turn-over time and 'age' of water in the dolomite aquifers and from it the ratio of the aquifer storage to the average annual recharge, which would provide an estimate of the storage water in relation to the annual recharge.

- Verify the bi-modal recharge and mixing model according to the simulations of selected springs for which ^{14}C measurements have been obtained over a long period.
- Derive a relationship between the rainfall and recharge that could be used to obtain the variability of monthly recharge without incorporating the threshold rainfalls.
- Compare the outcome of the ^{14}C model to using tritium and CFC as tracers and to reconcile the results and validate their use and reliability as environmental tracers.
- Simulate the propagation of contaminants through a dolomitic aquifer from the ^{14}C model.
- To check and validate the basic premise of the ^{14}C conceptual model, i.e. that
  - i) the recharge comprises a normal and direct component as is evidenced by the bicarbonate concentration of the spring water;
  - ii) the bicarbonate concentrations provide the key to the ^{14}C model and to establish it as an independent method of determining the recharge controls and the turnover times of water in the aquifer;
  - iii) the bicarbonate concentrations of springs could be used to obtain quantitative estimates of the average recharge of dolomitic aquifers where the CMB method (chloride mass balance) cannot be applied.
- Demonstrating the ^{14}C, CFC and tritium modelling as a significant contribution towards more effective utilization of the dolomitic aquifers and as a means to assess the impact of pollution of these valuable groundwater resources.

Section 2. ^{14}C simulation method

2.1 Use of ^{14}C as a natural tracer

The environmental radioactive carbon isotope ^{14}C is being introduced into the groundwater as bicarbonate, mainly through the action of carbon dioxide derived from root respiration on the dolomite (see Section 3). It is reasonable to assume that in spite of some delay there are no loss of tracer other than by radioactive decay, and in view that the residence time of water in the aquifer is short in comparison with the half-life of the radioactive ^{14}C (t1/2 = 5730 years), the ^{14}C can thus be treated as a conservative tracer.

In view of the fact that the input of the thermonuclear ^{14}C pulse is part of the rainfall recharge over the entire recharge areas of the springs, it allows a comparison of the groundwater response of the different dolomitic formations for both large and small aquifer systems and of the parameters that control the recharge. The latter incorporates the variability of rainfall and of differing surface-cover, ranging from congregates of rubble and soil to bare outcrops of dolomite of the different lithological substrata, varying in thickness and in area (see Figure 2 for the NW dolomite).

From measurements that have started around 1969 a series of intermittent single ^{14}C values over a period of 30 years have been obtained but no measurements prior to the start of the thermo-nuclear pulse have been obtained for any of the springs. Previous interpretation and simulation according to a uniform exponential mixing model proved to have been inconclusive and merely provided an indication of the range of residence times in the different dolomitic aquifers. (Talma and Weaver, 2003). However, using a new conceptual model that has been put forward by Bredenkamp and Van Wyk (2005) the reappearance of the ^{14}C has been successfully simulated. This provided the incentive to examine the model more thoroughly and assess the outcome of all dolomitic springs for which sufficient ^{14}C measurements have been obtained. In view of its potential and significance the Water Research Commission has approved the present study with the aims set out in the previous section. The dolomitic areas and most of the springs that have been included are shown in Figure 1.

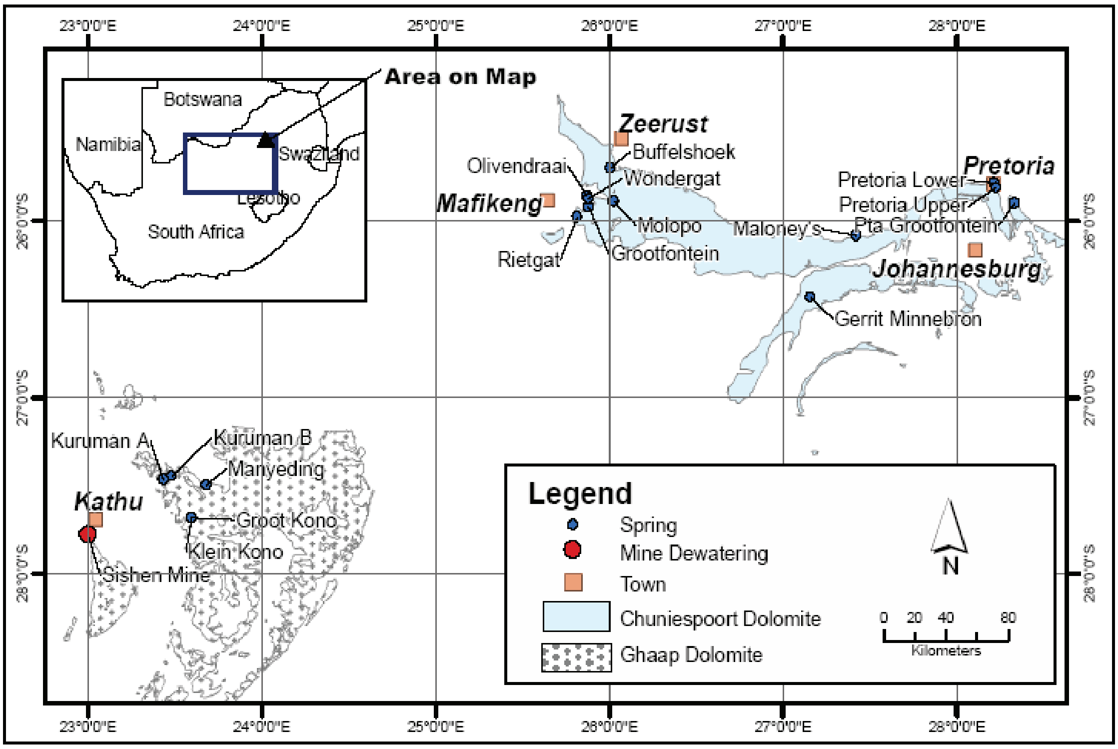


Figure 1. Locality of dolomitic springs of the Central, North-western and Eastern regions of the Republic of South Africa.

2.2 Estimation of recharge using environmental tracers in relation to other methods

Estimation of the recharge and its mixing with water in the aquifer is critical for reliable simulation of the ^{14}C response. The methods that are available for quantifying recharge of the karst aquifers depend on the different sources and areas of recharge. It remains essential to know each of the method's limitations in terms of applicability and reliability, especially in heterogeneous karst aquifers where its evolution exert a distinct influence on the groundwater recharge. Therefore, to comprehend the dynamics of a karst aquifer, it is necessary to understand the recharge processes and the hydrodynamic flow that are controlled by the permeability of the aquifer and exchange of water between the different water components. The following methods have been applied in the NW dolomite with varying success to estimate the recharge:

i) The *chloride mass balance method* (cf. CMB method – Beekman and Xu, 2003) provides the most independent estimate of recharge in an aquifer, provided that it is not contaminated and that the aquifer matrix (e.g. the dolomite in this case) does not add chloride to the ground water and that the chloride input from rainfall is adequately known. A reasonable estimate of the chloride content of the rainfall could be obtained from the regional relationship (Bredenkamp, 2000) and an updated version (In: Woodford and Chevallier, 2002) shown in Figures A1 and A2 in Appendix 2. However, as an extension to the present project, a new way to derive the chloride concentration in dolomitic aquifers has been devised (see Section 8.3). This has indicated that the regional relationship (presented by Bredenkamp et al., 1995) is overestimating the chloride input of the rainfall and therefore also the recharge. A thorough reassessment of the chloride of the rainfall is therefore essential and would need to be further examined in follow-up studies to the present project.

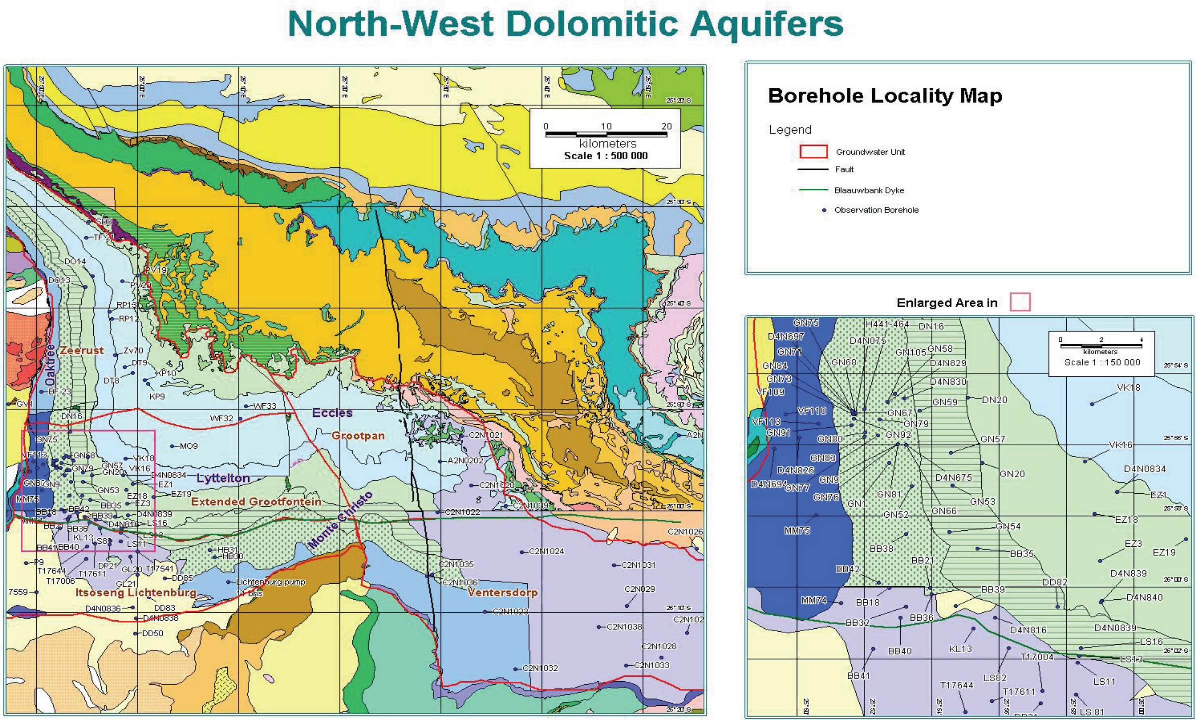


Figure 2. The typical lithostratigrapical sequence of the Malmani dolomitic of the North West Region showing the different dolomitic formations and numerous observation boreholes.

ii) *Conversion of spring flow to recharge*: Provided that the recharge area is known the flow of a spring or abstraction could be converted to an equivalent percentage of the annual average precipitation (water balance and equal volume method (Van Tonder and Xu, 2001). It is however not easy to accurately delineate the recharge area of a spring, especially in the dolomite where different sub-compartments with unknown contributions of leakage have to feed the spring discharge or sustain the rates of abstractions (see Figure 27).

iii) The *Cumulative Rainfall Departure* (CRD) and the Moving Average (MA) methods (cf. Bredenkamp et al., 1995; Bredenkamp, 2000; Bredenkamp, 2004) have provided a notable improvement in the estimation of the recharge. Both these methods showed good correlation with fluctuations of groundwater levels and spring flows and indicated an exponential increase in recharge as the rainfall increases. *These methods do not, however, yield absolute values for the recharge because of the interdependence between recharge and the specific yield of an aquifer*. An estimate of the average recharge coefficient (=b) could be obtained from the ratio of the chloride content of rainfall to that of the groundwater, but is dependent on the reliability of the chloride concentration of the rainfall and that no contamination of the chloride in the aquifer has occurred (refer CMB method -Beekman and Xu, 2003).

iv) *The use of natural ^{14}C and tritium concentrations*. Environmental ^{14}C and tritium has been applied with limited success in an investigation of the Grootfontein-Molopo compartment using classical hydrologic methods as well as environmental radiocarbon, ^{14}C, and tritium (^{3}H) to provide estimates of the annual recharge. However, the use of radioisotopes for quantitative estimations of recharge turned out to provide only a qualitative indication whether recharge is of recent origin or not.

v) *Fall-out of artificial tritium and ^{14}C from thermo-nuclear tests into the atmosphere* have been applied to estimate the recharge, e.g. from the

a) Propagation of *the environmental tritium in the unsaturated zone*. An estimate of the recharge is obtained from the depth to which the thermonuclear pulse of tritium has propagated in the unsaturated soil zone overlying the dolomitic aquifer (Bredenkamp et al., 1974), similar to the interpretation of chloride profiles. This assumed that the recharge is effectively a piston-like displacement of successive individual recharge events. Application of the method is limited to areas that are covered by a substantial thickness of soil, which is seldom occurring and is not representative of the aquifer as a whole.

b) *Reappearance of the environmental tritium and ^{14}C pulse in springs*. Examining the recharge and turnover of water in the dolomitic aquifers by means of ^{14}C and tritium that has been released from thermonuclear tests since 1955 into the atmosphere, which has caused an increase of about 60 % in the natural ^{14}C levels, provided mostly qualitative results (Bredenkamp and Vogel, 1967; Talma and Weaver, 2003). The most promising results have been derived for the Kuruman spring from the reappearance of the diluted ^{14}C pulse in the spring flow (Bredenkamp et al., 1995), but the hydrological rationale based on mixing of recently recharged water with an undefined component of old water was not justifiable, although a good fit has been obtained between the observed and simulated values. There were also major differences between the lag in response of the tritium and ^{14}C simulations, which were unresolved at the time.

The recent ^{14}C *simulation model* of the springs (Bredenkamp and Van Wyk, 2004) has been claimed to provide an independent method to derive the recharge coefficients and threshold rainfall to be exceeded before recharge could occur. A critical scrutiny of the method, however, revealed that it is essential to have a reliable estimate of the average recharge as a reference to yield the right recharge parameters (Vogel and Bredenkamp, 2005 *in publ.*). This again highlighted the importance of the CMB method, or deriving the recharge from the flow of springs from a well-delineated recharge area, to fix the recharge controls and parameters that have been obtained from the ^{14}C simulations of the springs.

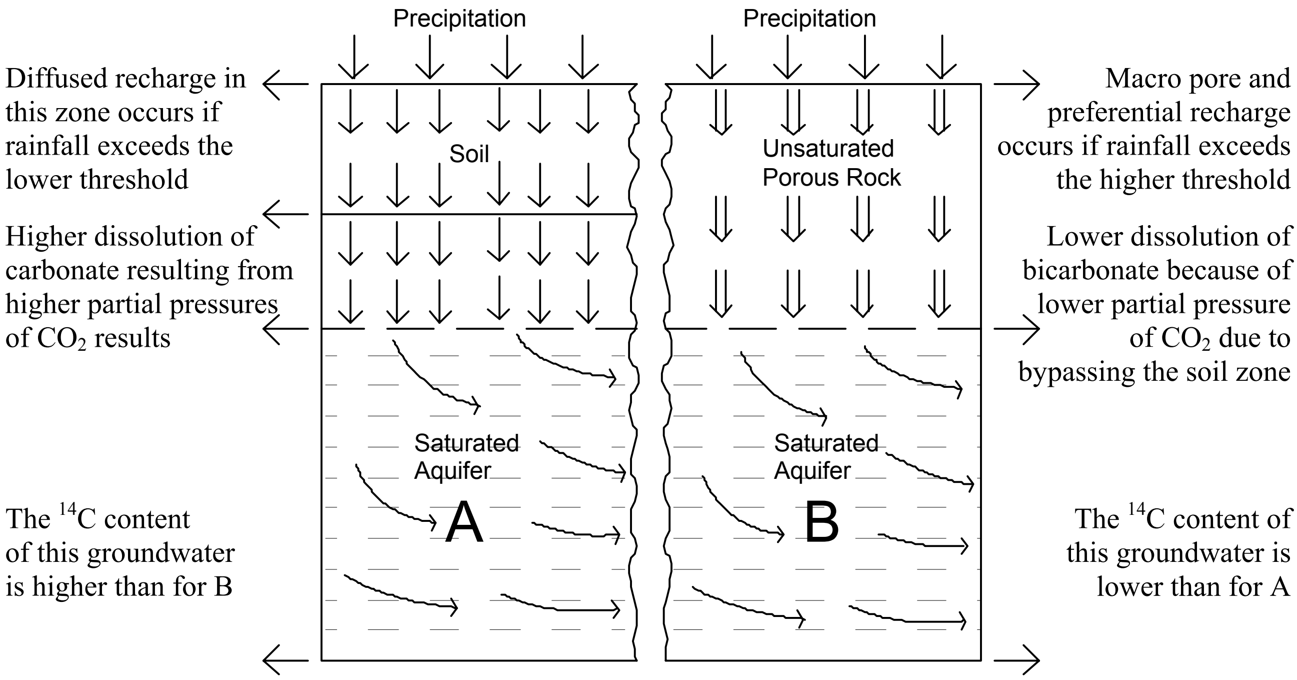
Estimation of recharge in the dolomite from the bicarbonate concentrations of the groundwater

According to Bredenkamp (2000 and 2004) the bicarbonate concentrations of dolomitic aquifers could provide a means of quantitative estimation of the average recharge. Therefore, from *the dual-recharge concept and optimising the model parameters to yield the best simulation of both the ^{14}C and the bicarbonate of the spring*, it was hoped that the ^{14}C model could be proven as an independent method to estimate the recharge and derive its controlling parameters.

Section 3. ^{14}C simulation model

3.1. Conceptual model

BIMODAL RECHARGE IN DOLOMITIC AQUIFERS



(1) $R_n = b_n\,(Rf > t_1)$

(2) $R_d = b_d\,(Rf > t_2)$

(3) $^{14}C = f(HCO_3)_{soil\ zone}$ (higher ^{14}C)

(4) $^{14}C = f(HCO_3)_{unsaturated}$ (lower ^{14}C)

Figure 3. Schematic diagram of the bimodal recharge that controls the variable recharge and input of ^{14}C in the simulation model.

The rationale of the bi-modal recharge is schematically presented in Figure 3 and the recharge components of the model are set out below and have been adjusted so that the average recharge corresponds to independent estimates of the average recharge derived from the CMB method:

i) In addition to the 'normal' recharge (e.g. diffused flow through the soil zone), a *recharge factor* that operates during periods of high rainfall is introduced. The latter represents the more direct macro-pore recharge. This produces a gradual exponential increase in the recharge as precipitation rises.

ii) A *cut-off* value to the monthly rainfall is applied to the 'normal' recharge component, while a significantly higher threshold applies to the high rainfall component. No water is contributed by the recharge component below these thresholds.

iii) Of the *monthly excess rainfall* values only a fraction reaches the groundwater table - the rest is lost by evapotranspiration.

iv) A further *weighting factor* is applied to the fractions. It increases/decreases as the precipitation of preceding months is higher/lower than the average and contributes to the exponential rise in recharge.

v) The relative amount of recharge is furthermore determined by the *average of the excess rainfall values* over a number of foregoing months.

vi) Since the hydrostatic pressure exerted by the elevation of the water table determines the discharge, the spring-flow is directly correlated with the monthly recharge.

The relative recharge of month i is thus given by:

$$R_i = \frac{aw}{u}\sum_{i=1}^{i=u}(Rf_i > t_1) + \frac{bw}{v}\sum_{i=1}^{i=v}(Rf_i > t_2) \quad \text{Eq. 1}$$

where

$(Rf_i > t_1)$ and $(Rf_i > t_2)$ are the precipitation values for month i greater than t_1 and t_2, respectively;

a and b are the respective fractions of the rainfall that reaches the saturated zone;

$w = \frac{1}{xRf_{ave}}\sum_{i=1}^{i=x} Rf_i$ is the weighting factor;

Rf_{ave} is the long term rainfall average;

u and v and x are the number of months over which the summation is carried out. In this application they could vary between 12 and 48 months.

3.2 Validation of the recharge estimations

The water table in one of the dolomitic compartments is exposed in the Wondergat sinkhole in the NW dolomite basin where several springs also occur (Figure 1). Regular measurement of the water level and of monthly rainfall has provided a record of the recharge response since 1922. This has been used to check the reliability of the recharge derived from the ^{14}C model. As Figure 4 shows, the appropriate adjustment of the model parameters produces a recharge record that closely correlates with the monthly water level fluctuations. The indication that the level of the Wondergat has reacted even before the average rainfall has risen, e.g. around 1974, could be attributed to a different rainfall in the recharge area of the spring as compared to that at the Wondergat, situated about 15 km from the spring. The more gradual recession of the water level of the Wondergat is caused by sustained recharge from overflow from higher lying compartments.

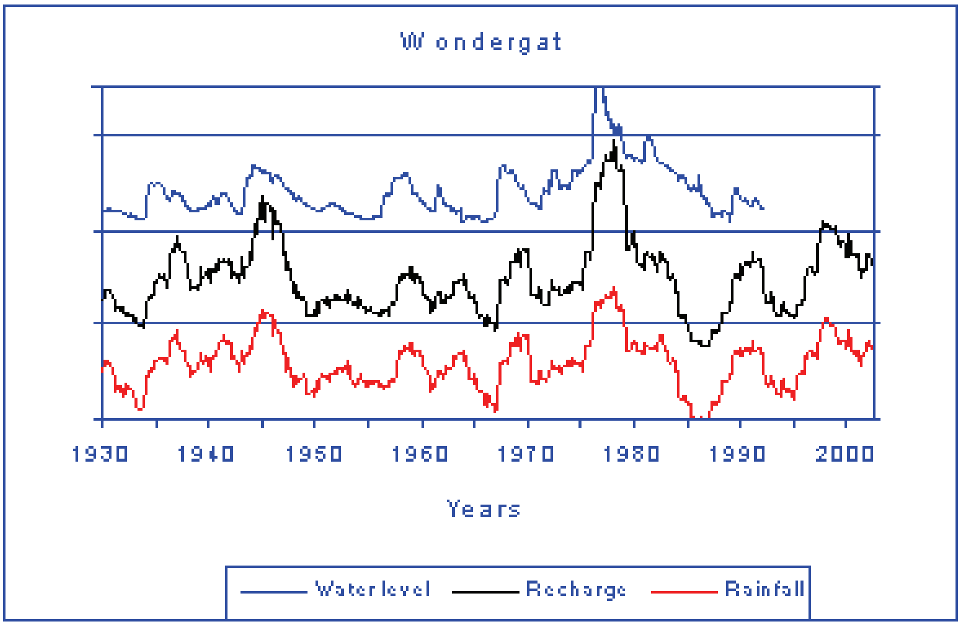
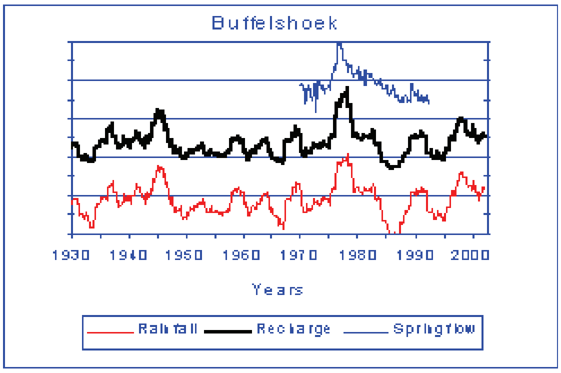


Figure 4. An illustrative representation showing the correspondence between the water level in the Wondergat sinkhole (top curve) and the simulated recharge. The bottom curve shows the three-year running average of the rainfall (arbitrary units as three variables cannot be displayed on two y-axis).

The model can also simulate a full series of spring flows from the rainfall records if the area of recharge is varied so that the average recharge corresponds to the CMB estimate, which, as will be shown, has overestimated the recharge (see Section 8.4.3). Accurate delineation of the recharge area is difficult but has been achieved for some of the springs, e.g. Buffelshoek eye, from detailed geophysical and water level surveys (Wiegmans, 2004). The discharge of a few of the springs has been monitored at different times in the past. The correlation between the simulated recharge and the measured discharge of two of these springs is shown in Figure 5.



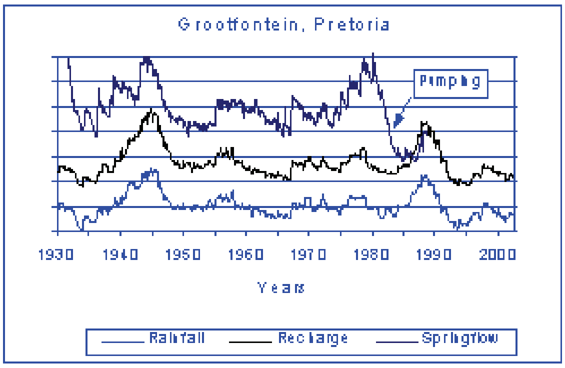


Figure 5. Correlation between the spring-flow records (top curve) and the simulated recharge for Buffelshoek and Grootfontein (Pretoria) springs. The bottom curve shows the 36 month running average of the rainfall (in arbitrary units).

Section 4. Rationale and structure of the ^{14}C simulation model

4.1 ^{14}C model

The large-scale atmospheric nuclear-weapon tests between 1954 and 1961 have caused a significant increase in the global inventory of ^{14}C that has since been slowly declining. This event has produced a large-scale pulse in the environment and the local record of this ^{14}C pulse can be used as a uniformly distributed tracer over the area. The ^{14}C content of several springs has been monitored on an irregular basis since 1967, so that a number of data points are available to calibrate the model. Unfortunately no measurements were done before the rise in the atmosphere level due to the nuclear weapon tests.

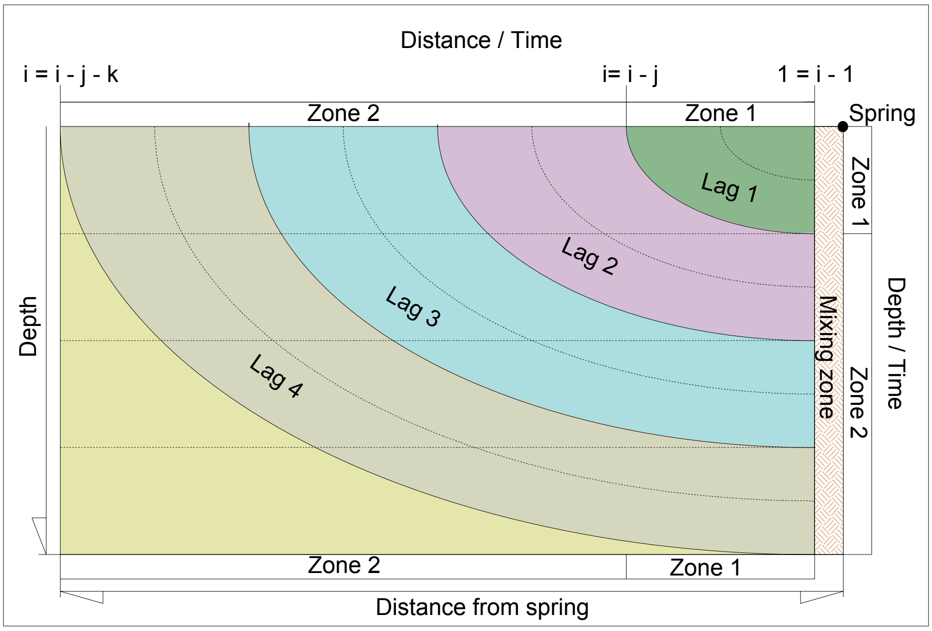


Figure 6. Schematic diagram of the flow and mixing of groundwater through a section of aquifer, according to the conceptual model; the recharge over the period 0 to j represents the shallow recharge to the spring and from j to k the deep flow recharge component.

The model to simulate the ^{14}C in the spring discharge is an extension of the Moving Average Model to derive the recharge. It has the following features:

i) The *relative ^{14}C content of the two components* of the recharge is calculated in a similar manner as for the actual amounts of the recharge. Thus the monthly value of the atmospheric ^{14}C times the excess rainfall amount is averaged over several previous months and multiplied by the fraction relating to the dilution of the ^{14}C during the dissolution of carbonate. The two components thus obtained are added together and divided by the total recharge to give the ^{14}C content of the water reaching the water table.

ii) The aquifer as a whole is treated as *two well-mixed boxes*, a shallow box that contains the recent recharge and rapidly moves towards the spring outflow, and a deeper one that represents the average preceding recharge over several decades, as is illustrated in Figure 6.

iii) At the spring *several multiples of the deep box* mix with the water from the shallow box to attain the ^{14}C of the spring discharge.

iv) A *final lag-time* of up to a few years is introduced to all the water. It mainly represents the time lag in the unsaturated zone, as well as a possible delay in the transmission through the aquifer.

The ^{14}C content of the water in month i is thus

$$C_i = \frac{1}{p+1}\left(\frac{gaw}{u}\sum_{i=i-1}^{i=i-j} A_i(Rf_i > t_1) + \frac{hbw}{v}\sum_{i=j-1}^{i=j-k} A_i(Rf_i > t_2)\frac{1}{R_i} + pC_{i-1}\right) \quad \text{Eq. 2}$$

Where A_i is the ^{14}C value of atmospheric CO_2 in month i;

g and h are the fractions of A_i in the two components of the recharge;

p is the multiple of deep water that admixes with the shallow water fraction from the spring;

the summation period (i-j to i-j-k) over which the deep water is averaged is varied (usually several hundred months); and

j is the number of months preceding month i (here taken as j = 36 but it could be as low as 12 months). The value of j should be a multiple of 12, i.e. representing contributions over multiples of 12 months and determining the shallow flow.

4.2 Implementation of ^{14}C model

The model parameters are adjusted interactively until the best simulation of the measured ^{14}C values has been obtained, i.e. producing the smallest sum of the differences squared. The various parameters controlling the outcome of the simulation is shown on worksheet 1 of the Excel program representing the ^{14}C model that is attached in Appendix 3. The following procedure is used to obtain the best simulation:

(i) Insert an *approximate recharge* coefficient for the normal (diffused) and preferential/ macro-pore recharge controlled by the high threshold recharge components (direct/ preferential).

(ii) Insert the *threshold rainfall values* controlling the normal (diffused) and direct recharge.

(iii) Select a *provisional ^{14}C factor* for the normal (diffused) and macro-pore (direct recharge) components as follows:

- A value in the range of 0.75 to 0.90 for the normal recharge if the bicarbonate concentration of the spring's water is between 240 to 300 mg/l.
- A value in the range of 0.5 to 0.7 for the direct recharge component, i.e. if the bicarbonate concentration is between 100 and 230 mg/l.

(iv) Use the set of graphs (Figure 7) indicating the type of response to adjust *the deep flow multiple,* to improve the goodness of fit. If the measured ^{14}C values show a distinct declining trend, enter a multiple of about 1 to 2 for the deeper flow component, and a value ranging between 2 and 5 if the measured ^{14}C values do not vary significantly.

(v) Incorporate the *final lag-period* by which the entire simulated pulse has to be shifted to obtain the best fit. This lag is regarded to indicate the delay of recharge in the unsaturated zone before it reaches the saturated flow regime, or due to matrix diffusion. This implies that the measured ^{14}C actually represent the values of months shifted backwards by the final lag period, i.e. having been caused by earlier rainfall.

(vi) Adjust the various parameter values with the corresponding scrolls until a minimum error has been obtained. The average error for each spring, i.e. the 'Error$_{av}$ =' is the sum of the differences squared.

(vii) A close comparison between the average recharge of the model and that obtained from the CMB estimate is required. The same applies to the measured and simulated bicarbonate concentrations of the springs that could hopefully establish the independency of the ^{14}C method.

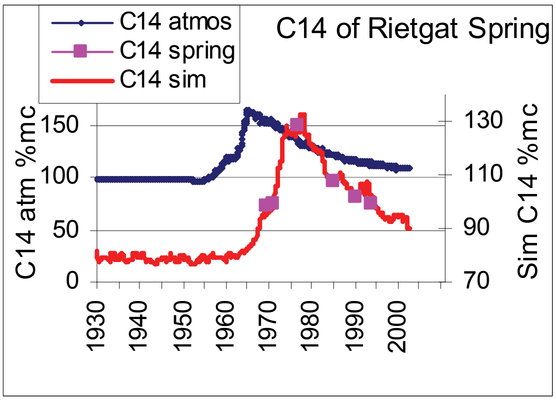


Figure 7a. Response with a zero deep-flow.

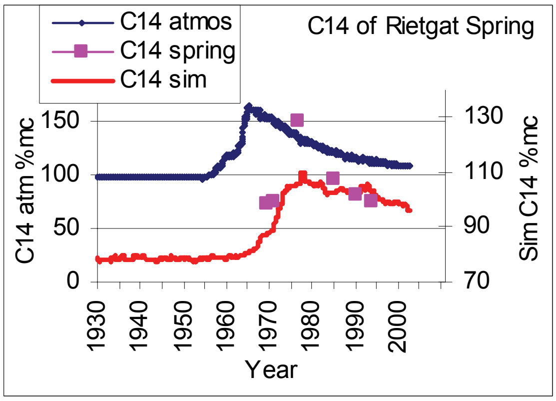


Figure 7b. Response with one multiple of deep flow.

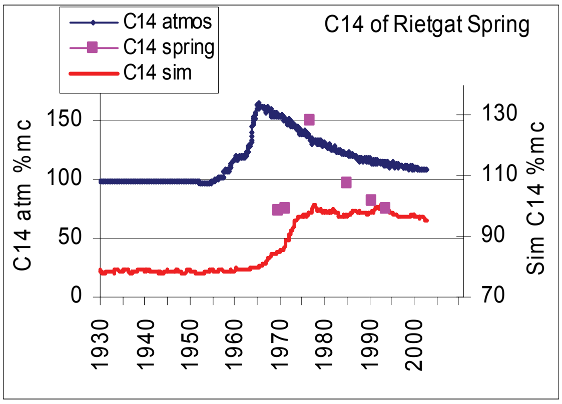


Figure 7c. Response with 2 multiples of deep flow.

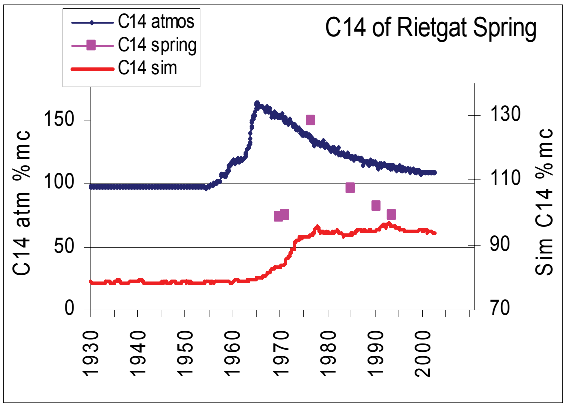


Figure 7d. Response with 3 multiples of deep flow.

As is evident from the set of figures (Figure 7) an increase of the deeper flow component reduces and flattens the simulated ^{14}C pulse because of the predominance of the deeper flow.

4.3 Application of the model

The modelling has in the present project been extended to all the dolomitic areas shown in Figure 1, which represent different types of dolomite and constitute important sources of water in the form of springs, rural and township water supplies and also irrigation abstraction. Naturally the larger the number and spread of ^{14}C measurements for a spring over a long period, the more reliable the ^{14}C model is regarded to be.

A main shift in the present study has been to determine the impact of variation of the relative contributions of ^{14}C from the shallow and deep recharge components (period 1 and 2 respectively). The length of both periods has been varied over a wide range as compared to the study of Bredenkamp and Van Wyk (2005) in which the first period had been fixed at about 60 months. It turned out that in several instances an improved simulation could be obtained if period 1 is decreased from 48 to 12 months as is illustrated for Buffelshoek eye (see Table 2), however, the period over which the monthly recharge contribution is averaged also reduces the variability of the ^{14}C of period 1. For this spring the best simulation has been obtained for period 1=24 months.

In order to ensure that all the water is accounted for in the mixing model, arguably period 1 should not be less than the period over which the monthly recharge contributions of ^{14}C is averaged (see Section 4.1). That would ensure that all the recharge, which has occurred during period 1, would contribute to the ^{14}C mix of the two components of recharge. However, as some of the shallow recharge might still be delayed in the unsaturated zone, it could mix some time later with the more direct recharge that has already reached the saturated zones. According to Figure 6 the contribution from period 1 (i.e. from zone 1, which is the shallow component) mixes with the average ^{14}C of recharge of period 2 that constitutes the deep flow. Thus the ^{14}C contribution of recharge from points farther from the spring will lag that of points closer to the spring outlet. As the deeper component (i.e. from zone 2) is also controlled by the recent recharge and is greater than that of the shallow contribution from period 1 (i.e. zone 1), the deeper component is incorporated as a multiple of the shallow component.

The model at all stages essentially conforms to a piston-like displacement of the mixed recharge of each month even when it reaches and flows through the saturated zone of the aquifer. In this series of monthly recharge events, the hydrostatic pressure, i.e. water level in the aquifer, controls the relative contributions of the deep as well as the shallow components to the spring flow. The latter responds to the rainfall that has occurred over a number of preceding months and more directly to the high-threshold recharge. The recharge of the ^{14}C model therefore conforms to the MA relationship, shown to correspond well to the water level fluctuations and spring flows (see Figure 4).

For Buffelshoek spring, which proved to be the key to reliable simulation of ^{14}C, the following could be highlighted (refer Table 2):

> The *weighting factor* of the monthly recharge that is controlled by the average rainfall for a period of n-months prior to a specific month would amplify the recharge of months of high rainfall and will lower it for months with lower than average precipitation.
>
> The *final lag period* in the case of Buffelshoek eye varies depending on the averaging periods that are used to calculate the monthly ^{14}C inputs of the rainfall recharge. According to Table 2, the overall lag is 19 to 20 months if the rainfall averaging periods is 48 to 36 months and the multiples of the deep component is smaller. For period 1 and rainfall with averaging periods of 24 and 12 months, better simulations have been obtained but the final lag time has respectively increased to 75 and 69 months with the multiples changing accordingly. This already provides an indication of the role and significance of movement of water through the unsaturated zone overlying an aquifer that will be discussed in Section 9.1.
>
> The *multiples of deep flow* (see Table 2) remain effectively the same irrespective of the averaging periods of the rainfall and of the shallow and deep flow components.

Table 2. The variables and typical results for Buffelshoek spring.

SPRINGS	Buffelshoek	Buffelshoek	Buffelshoek	Buffelshoek
Minimum Residual Squared	**3.05**	**3.79**	**1.85**	**2.38**
Low threshold (mm)	8.8	10	9	9
High threshold (mm)	68	62.2	64.4	65.8
Recharge factor (N) – normal diffused recharge	0.127	0.128	0.121	0.124
Recharge factor (D) – recharge bypassing the soil zone	0.069	0.058	0.068	0.068
^{14}C factor (N) – for the normal diffused recharge	0.844	0.83	0.84	0.84
^{14}C factor (D) – for recharge bypassing the soil zone	0.587	0.59	0.59	0.59
Multiple of deep flow	**3.04**	**2.77**	**3.57**	**3.87**
Period 1 – shallow flow	48	36	24	12
Period 2 – deep flow	328	334	328	328
Start year	1922	1922	1922	1922
Start month	1	1	1	1
Rainfall series (months)	937	937	937	937
No. of months included in averages of:				
Recharge weighting	48	36	24	12
^{14}C – lower threshold (months)	48	36	24	12
Average surplus – lower threshold (months)	48	36	24	12
Average surplus – high threshold (months)	48	36	24	12
^{14}C – high threshold (months)	48	36	24	12
Final lag ^{14}C (months)	**19**	**20**	**75**	**69**
Simulated HCO3 of spring (mg/l)	237.84	231.7	237.27	238.36
Measured HCO3 (mg/l)	228.8	228.8	228.80	228.80
Recharge area (km^2)	25	26.8	25	25
Cl of spring (mg/l)	4.5	4.5	4.5	4.5
Cl recharge coefficient	0.124	0.124	0.124	0.124
^{14}C recharge coefficient	0.124	0.124	0.124	0.124

Section 5. ^{14}C simulations of different springs

5.1 General

The outcome of the latest ^{14}C modelling has been grouped according to the dolomitic regions in which the springs are located. This has allowed a comparison of the recharge and other parameters in relation to the characteristics and sizes of the recharge areas that feed the various springs. The best ^{14}C simulations of each area are shown as a separate set of graphs in Appendix 2 (B to F) and the parameter values are listed in a corresponding table in the main report, i.e.:

- Figure B1-B8 and Table 3 – Grootfontein/Zeerust area of the NW dolomite
- Figure C1-C4 and Table 4 – Schoonspruit-Maloneys area of the NW dolomite
- Figure D1-D4 and Table 5 – Pretoria dolomite

- Figure E1-E2 and Table 6 – West Rand dolomite
- Figure F1-F4 and Table 7 – Kuruman dolomite
- Figure G1 and Table 9 – Sishen dolomite
- Figure H1-H8 Table 8 – Rainfall-recharge regressions for selected springs

5.2 Bo Molopo area – NW Dolomite

(See Figures B1-B8 in Appendix 2 for ^{14}C simulations.)

The Grootfontein, Lichtenburg and Zeerust dolomite has been investigated since about 1963 using a variety of methods (see Section 1). The flows of springs issuing from these aquifers have been monitored over many years. Irregular ^{14}C measurements have also been obtained and have been simulated with the new model. The individual graphs showing the outcome of the modelling appear in Appendix 2 and the recharge parameters are listed in Table 3. The following can be commented on the parameter values:

> The *low threshold* values of the various simulations presents an integrated value for the entire aquifer and varies in accordance with the thickness and material covering the dolomite aquifer. As it controls the ease of infiltration to the aquifer deeper down, the threshold should be small if the overburden is shallow and it should be higher if the soil thickness is greater. The regional average value of the low threshold for this dolomite is about 21.4 mm per month but it varies from as low as 9 mm (Buffelshoek eye) to 40 mm for Grootfontein eye. The low threshold values are consistent with the thin chert-rich soil covering the predominantly Eccles dolomite, i.e. of the Buffelshoek aquifer, whilst the higher value, e.g. of Grootfontein conforms to an overburden of soil and chert up to 30 metres deep.
>
> As is evident from Table 3 the *high threshold* values are surprisingly similar for the entire area, varying between 51 and 77 mm/month with an average of 67 mm/month. This indicates that it is a characteristic of the recharge of the aquifer controlled by rainfall intensity rather than by the characteristics of the overburden.

^{14}C factors for recharge

The *^{14}C factors* used with both the low and high thresholds of rainfall to derive the ^{14}C concentration of the spring water show the following pattern:

- It has an average value of 0.86 of the input ^{14}C, which is in line with that of recent water deriving its ^{14}C from the soil zone.
- For the recharge that partially or fully bypasses the soil zone the fraction varies between 0.5 (for Molopo eye) to 0.68 (for Lichtenburg spring), with an average of 0.62. Although this water, in terms of the classical dating interpretation, would appear to be more than a thousand years old it is in fact young water.

Multiples of the deep flow component mixing with the shallow recharge

This factor controls the relative mixing between the deep and shallow flow components to yield the ^{14}C content of the spring water. The multiples appear to be related to the volumes of water contained in the aquifer and are higher when the depth of the aquifer and the recharge area feeding a spring is large. It could also be controlled by influx of water (leakage or overflow) from higher-lying compartments.

Mixing periods

To obtain the best simulation, the shallow and deep flow components (period 1 and 2 respectively) are of critical importance. According to Table 3, period 1 varies between 12 to 48 months, but for most of the simulations it is has been 36 months. As is evident for Buffelshoek eye (Table 2), good simulations could be obtained if period 1 is varied between 12 to 36 months. Correspondingly, smaller multiples of the deep component are required if period 1 is larger.

Varying the averaging periods of rainfall

The rainfall periods to obtain the effective recharge of a particular month are varied so as to obtain the best simulation of ^{14}C. This is in accordance with a conceptual model that more recharge occurs when the rainfall over a preceding period is higher than the long-term average rainfall and vice versa (Bredenkamp, 2004). Thus the following is incorporated:

- A *rainfall-weighting factor*: This adjusts the recharge factor according to the rainfall over the averaging period being higher or lower than the long-term average as has been applied for reliable simulation groundwater levels and the flow of dolomitic springs (Bredenkamp, 2000 and 2003).
- An averaging period to obtain the recharge of a specific month from the rainfalls in excess of the low threshold of preceding months, i.e. the diffused recharge via the soil. This period varies between 24 and 48 months being higher for larger recharge areas and vice versa.
- An averaging period for recharge associated with rainfalls in excess of the high threshold, i.e. for recharge essentially bypassing the soil zone. Although this period could be different from the low threshold case, the averaging periods have been made the same but constitute multiples of a year.

Table 3. Results of Dolomitic Springs July 2005

	A	B	C	D	E	F	G	H	I	J	K	L	M
SPRINGS	Buffelshoek	Olievendraai	Grootftn Molopo	Molopo	Rietgat	Vergenoeg	Doornplaat	Doornftn	Paardevlei upper	Lichtenburg	Dinokana Upper	Stinkhout boom	Molopo area
Minimum Residual Squared	3.2	5.8	29.7	19.2	10.3	6.2	3.3	5.4	2.8	7.4	0.4	6.49	
Low threshold (mm)	12.5	15.2	38.2	31.9	26.8	11.7	21.5	25.1	10.9	21.3	24.1	16	21
High threshold (mm)	63.9	66.6	68.8	75.7	51.4	77.7	67.4	66.2	67.3	76.3	66.1	59.7	68
Recharge factor (N)	0.112	0.097	0.084	0.084	0.065	0.098	0.068	0.073	0.078	0.077	0.108	0.101	0.093
Recharge factor (D)	0.065	0.012	0.114	0.151	0.034	0.049	0.017	0.036	0.031	0.063	0.066	0.067	0.045
^{14}C factor (N)	0.83	0.896	0.853	0.906	0.881	0.831	0.851	0.85	0.894	0.897	0.842	0.832	0.865
^{14}C factor (D)	0.592	0.65	0.551	0.503	0.682	0.658	0.619	0.649	0.565	0.687	0.627	0.595	0.619
Multiple of deep flow	**3.19**	**1.08**	**4.12**	**7.6**	**0**	**2.48**	**3.96**	**1.5**	**2.03**	**1.74**	**6.58**	**2.07**	**3.09**
Period 1 (months)	1	24	36	48	36	36	24	36	36	36	36	36	35
Period 2 (months)	348	349	338	539	233	304	346	304	304	350	304	304	336
Start year	1922	1922	1922	1922	1922	1922	1922	1922	1922	1922	1922	1922	
Start month	1	9	1	1	1	1	9	1	1	1	1	1	
Months for long term average	937	937	937	937	937	937	937	937	937	937	937	937	

Table 3 continues on next page

Table 3. (continue) Results of Dolomitic Springs July 2005

	A	B	C	D	E	F	G	H	I	J	K	L	M
SPRINGS	Buffelshoek	Olievendraai	Grootftn Molopo	Molopo	Rietgat	Vergenoeg	Doornplaat	Doornftn	Paardevlei upper	Lichtenburg	Dinokana Upper	Stinkhout boom	Molopo
No. of months included in averages of:													
Rainfall weighting	25	24	24	48	24	36	24	36	36	36	36	36	
^{14}C – lower threshold (months)	12	24	36	48	36	36	24	36	36	36	36	36	
Average surplus – lower threshold (months)	12	24	36	48	36	36	24	36	36	36	36	36	
Average surplus – high threshold (months)	12	24	36	48	36	36	24	36	36	36	36	36	
^{14}C – high threshold (months)	12	24	36	48	36	36	24	36	36	36	36	36	
Final lag ^{14}C months	**74**	**20**	**57**	**13**	**86**	**15**	**26**	**140**	**97**	**14**	**92**	**48**	**55.5**
Turnover time (years)	11.6	8.6	12.8	21.9	1.5	10.6	12.5	9.1	10.0	10.8	12.5	10.0	11.0
Simulated HCO3 (mg/l)	228.6	283.2	222.1	247.3	238.8	240.5	256.7	262.5	266.4	265.4	232.9	222.3	
Measured HCO3 (mg/l)	228.8	284	228	199	285	244	284	239	266.5	270	237	229	
Recharge area (km^2)	32	26.8	92	357	38	71	32.1	71.4	71	276	196	11	285
Cl of spring (mg/l)	4.5	7.7	6.4	5.0		5.8	5.860	7.68	7.3	8	7	5.6	
Cl Recharge coefficient	0.124	0.072	0.089	0.116	0.07	0.096	0.096	0.074	0.075	0.07	0.094	0.10	0.083
^{14}C recharge coefficient	0.124	0.07	0.089	0.116	0.07	0.095	0.096	0.074	0.075	0.07	0.094	0.104	0.082

Final lag

The final lag period represents the number of months by which the entire simulated series has to be shifted to obtain the best fit. The lag apparently accounts for water that is contained in the unsaturated portion of the aquifer, before entering the hydrodynamic flow regime of the aquifer. The lag varies from less than 20 months (in the case of Doornplaat, Molopo, Vergenoeg and Lichtenburg eyes) to 57 months for Grootfontein and 74 months for Buffelshoek. However, rather surprisingly for Rietgat eye, a large final lag of 86 months had to be incorporated in spite of the outcome that no deep-flow component is involved. The reason for this appears to be that the recharge occurs from the denser Oaktree dolomite, which, in the recharge area, is overlain by a thick layer of low-permeability calcrete with higher water content. This calcrete, according to the piston-like displacement, effects a greater lag.

The large final lag times in the case of springs in the Zeerust area, i.e. Stinkhoutboom (48 months), Upper Dinokana (92 months), Paardevlei (96 months), and Doornfontein (140 months), is still unresolved. This lag could possibly also be related to the delayed response of overflow from higher-lying compartments, which could be represented by a mixing model similar to that shown in Figure 6 with some of its recharge leaking or overflowing to the lower lying compartment.

5.3 Springs in the Marico-Schoonspruit dolomite area

(See Figures C1-C5 in Appendix 2 for ^{14}C simulations.)

The ^{14}C responses of four major springs issuing from this dolomitic area have been simulated, i.e.

- The Marico Grootfontein, with a high flow – 5.95 mil. cub. m/annum (Bredenkamp, 2004).
- Schoonspruit eye with the highest flow of all the dolomitic springs in the RSA (Veltman, 2003). This spring does not emerge as a point source but oozes at several points in the low-lying area before being finally measured at a weir collecting the total discharge.
- Upper eye of Mooi River: The spring probably receives part of its recharge from the Magaliesberg range in addition to the recharge from the dolomite.
- Maloneys eye: A large spring issuing from the edge of the dolomite and a significant portion of the flow is probably derived from recharge from the quartzitic Magaliesberg. This is corroborated by the anomalously low bicarbonate concentration of the spring (similar to the Grootfontein in the Pretoria dolomite).
- Renosterfontein: This spring has been included in this group because of low bicarbonate concentrations typifying a non-dolomitic spring. The spring has been contaminated, which allows the pollution to be examined according to the ^{14}C flow/mixing model (see Section 8).

The parameters of the ^{14}C simulations of Marico-Schoonspruit are listed in Table 4.

Comparison of ^{14}C results of Marico springs

Low threshold rainfall: Varies between 19 mm and 37 mm.

High threshold rainfall: Varies between 43 mm for Renosterfontein and 80.3 mm for Maloneys eye. These two springs are probably not dolomitic springs as the high and low ^{14}C factors are not typical of dolomitic formations, which are also confirmed by the low bicarbonate concentration of the spring water.

Table 4. Summary of ^{14}C simulation results of Marico-Schoonspruit area

SPRINGS	Marico Grootfontein	Schoonspruit Eye	Upper Mooi River eye	Maloneys Eye	Renoster-fontein eye
Minimum Residual Squared	**6.8**	**24.3**	**14.9**	**4.2**	**5.2**
Low threshold (mm)	18.8	22.5	18.3	37.2	20.1
High threshold (mm)	74	61.5	56.6	80.3	20.1
Recharge factor (N)	0.150	0.083	0.12	0.024	0.074
Recharge factor (D)	0.11	0.030	0.037	0.047	0.0012
^{14}C factor (N)	0.684	0.845	0.704	0.57	0.689
^{14}C factor (D)	0.548	0.67	0.582	0.554	0.5
Multiple of deep flow	**1.15**	**1.88**	**4.72**	**6.83**	**5.7**
Period 1 – shallow flow	36	24	12	84	60
Period 2 – deep flow	350	460	400	548	500
Turn over time (yrs)	7.67	12.18	13.39	17.27	15.93
Start year	1922	1922	1922	1922	1922
Start month	1	8	8	1	8
Months for long term average	946	946	946	946	937
Turnover (years)	**8.8**	**12.2**	**13.4**	**16.1**	**15.9**
Recharge weighting (months)	36	24	12	76	24
^{14}C – lower threshold (months)	36	24	12	48	24
Average surplus – lower threshold (months)	36	24	12	48	24
Average surplus – high threshold (months)	36	24	12	48	24
^{14}C – high threshold (months)	36	24	12	32	24
Final lag (months)	**23**	**11**	**60**	**46**	**33**
Simulated HCO3 of spring (mg/l)	151.9	246.6	169.7	96.0	167.4
Measured HCO3 (mg/l)	140	267	231	130	215
Recharge area (km^2)	253	890	461	500	
Cl of spring (mg/l)	4.1	10	6	3.3	
Cl recharge coefficient	0.15	0.063	0.105	0.12	0.12
^{14}C recharge coefficient	0.15	0.067	0.11	0.12	

The reliable simulation of the bicarbonate concentrations of the Schoonspruit spring indicates that the ^{14}C factors related to the low and high threshold rainfalls are in accordance with the postulated two-component recharge. For Maloneys eye the simulated bicarbonate (96 mg/l) is lower than the measured concentration of 130 mg/l, but for Upper Mooi River and Marico-Grootfontein eyes there is reasonable correspondence.

For these springs the recharge estimates obtained from the ^{14}C model have also been adjusted to match with recharge derived from the chloride mass balance (CMB).

The multiple factor indicating the admixture of the deep flow component of recharge is highly variable and is:

- the highest (6.8) for Maloneys eye followed by 5.7 for Renosterfontein eye.
- the lowest for Marico Grootfontein eye (1.15), which is a rather surprising outcome as the spring flow is sustained even during prolonged periods of below average rainfall, which indicate a substantial reservoir of water.
- 1.88 for Schoonspruit indicating a small component of deep flow, whilst for Upper Mooi River eye the deep flow (4.7) is larger than expected, which probably represents a large contribution of recharge from higher lying areas.

The averaging periods of rainfall of the first four springs range from 36 to 48 months but for Upper Mooi River the best simulation has been obtained for 12 months.

5.4 Springs in the Pretoria Dolomitic Area

(See Figures D1-D5 for ^{14}C simulations in Appendix 2)

Four major springs ooze from the Pretoria dolomitic basin (shown in Figure 8) with the Upper and Lower Fountains being the largest and they are still being utilized for the water supply of Pretoria. Next are the Grootfontein east of the Rietvlei Game Park and the Sterkfontein eye. The flows of three smaller springs at Rietvlei (Rietvlei 1 and 2 and the Erasmus fountain) are also linked to the water supply of Pretoria.

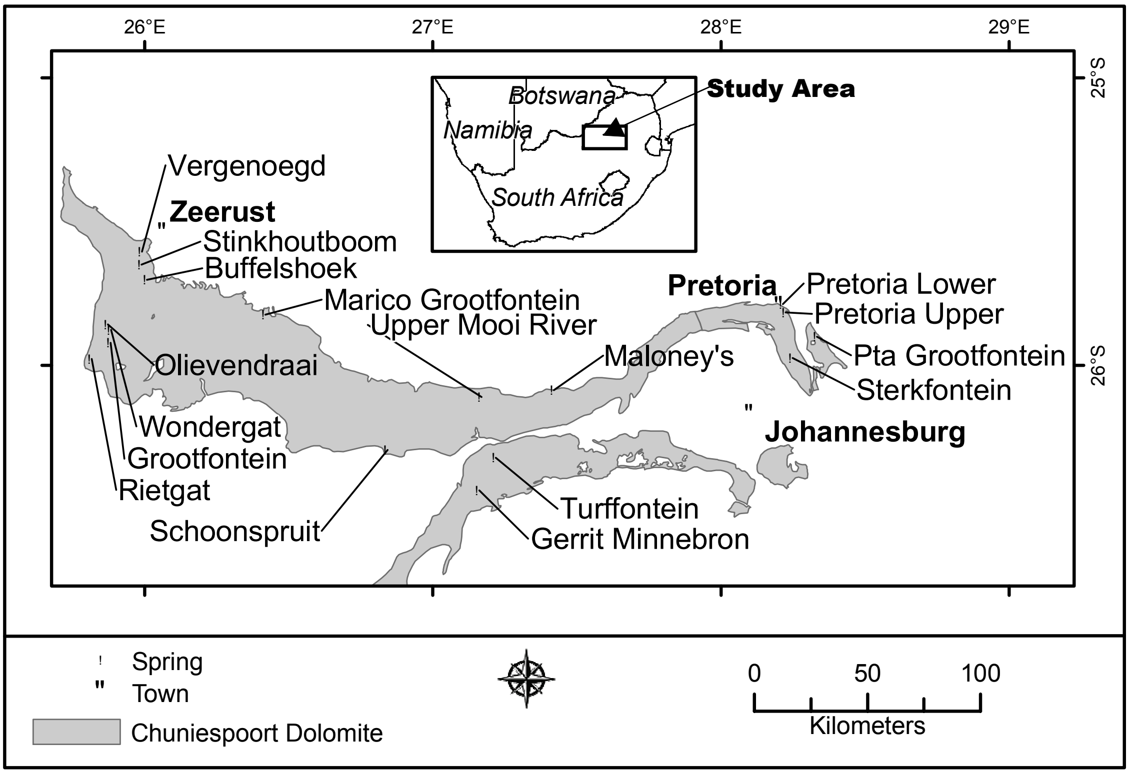


Figure 8. Locality of dolomitic springs in the northern part of the RSA.

Pumping from the Rietvlei dolomitic aquifer has affected the flow of the Grootfontein spring and has complicated the interpretation of the ^{14}C results. Bredenkamp (2000) has indicated that the abstractions from these boreholes have reduced the flow of the springs but it has not changed the isotopic concentration of the remaining outflow.

The results of the ^{14}C simulations of the Pretoria springs that have been monitored are listed in Table 5 and the individual graphs depicting the goodness of the fit between the observed and simulated ^{14}C values appear in Figures D1 to D5 in Appendix 2.

Table 5. Results of ^{14}C simulations of Pretoria Springs

SPRINGS	Erasmus Spring	Grootfontein Rietvlei Spring	Pretoria Upper fountain	Pretoria Lower fountain	Sterkfontein
Factors Minimum	27.6	3.2	6.0	30.8	6.7
Lower threshold (mm)	22.2	23.5	11.5	6.7	23.2
Higher threshold (mm)	79.3	61.4	64.4	67	69
Recharge factor (N)	0.15	0.15	0.116	0.116	0.091
Recharge factor (H)	0.028	0.084	0.057	0.048	0.065
^{14}C factor (N)	0.588	0.545	0.776	0.805	0.792
^{14}C factor (H)	0.5	0.504	0.525	0.541	0.653
Multiples of the deep flow	**17.93**	**4.29**	**11.99**	**5.24**	**6.18**
Period 1 – shallow flow	12	36	36	36	36
Period 2 – deep flow	500	329	435	435	480
Start year	1922	1922	1922	1922	1922
Start month	2	2	2	2	2
Months for long term average	946	946	946	946	946
Turnover (years)	**20.3**	**12.7**	**18.3**	**16.8**	**18.8**
Rainfall weighting (months)	12	36	36	36	36
^{14}C – lower threshold (months)	12	36	36	36	36
Surplus – lower threshold (months)	12	36	36	36	36
Surplus – higher threshold (months)	12	24	36	36	36
^{14}C – higher threshold (months)	12	24	36	36	36
Final lag (months)	**6**	**61**	**60**	**71**	**7**
Simulated HCO3 of spring (mg/l)	107.3	79.8	192.7	214.2	208.5
Measured HCO3 (mg/l)	110	117	197	197	194
Recharge area (km^2)		28.7			
Cl in rainfall mg/l	4.8	4.8		5.0	
^{14}C recharge coefficient	0.13	0.13		0.12	0.094
Cl recharge coefficient	0.13	0.13		0.12	0.11

Discussion of ^{14}C results of Pretoria dolomite

A distinct difference is that the bicarbonate concentrations of the Erasmus and Rietvlei springs are much lower than that of the Pretoria Fountains. As in the case of Maloneys eye the Grootfontein and Erasmus springs in the Rietvlei aquifer, probably derive their recharge predominantly from the quartzite and not from the dolomite. This is corroborated by the ^{14}C factors of both the normal recharge and high recharge component. This also conforms to the low threshold rainfall value that controls the normal recharge via the soil and vegetation zone, indicating that recharge occurs easily. The high threshold value controlling recharge that bypasses the soil zone is fairly similar to that of all the other dolomite terrains and is about 68 mm per month.

The *mixing period* of the shallow-recharge contribution to the spring flow of Grootfontein is about 36 months and for the deeper flow it is 329 months. The high *multiple of deep water* that admixes with the shallow recharge in the case of Erasmus spring (17.9) is anomalously high, however, the measured and simulated bicarbonate concentration of Erasmus eye compares well as do the chloride and ^{14}C recharge estimates.

The chloride concentrations of the Upper and Lower springs of Pretoria Fountains have been contaminated and therefore does not provide an independent estimate of the recharge (see Figure 9).

The *final lag periods* that have been incorporated in the ^{14}C simulations are much smaller for the Erasmus and Sterkfontein springs, which indicate a quick response to recharge. This is quite acceptable in view of these springs being located in a drainage depression often carrying surface flow.

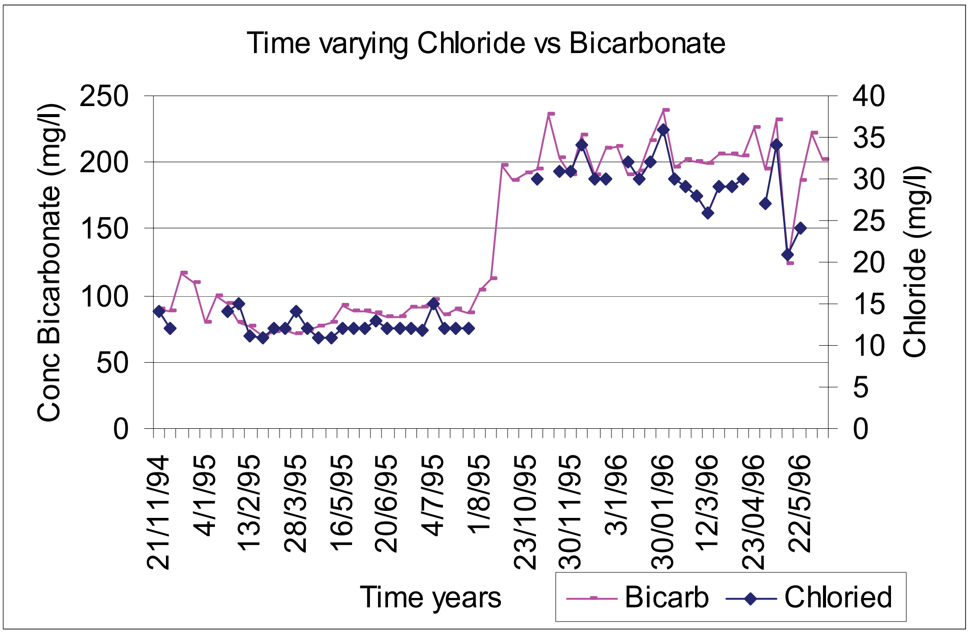


Figure 9. Chloride vs bicarbonate for Pretoria Springs indicating that pollution has occurred. The reason for the sudden change in the water quality should be ascertained.

5.5 Springs in the West Rand dolomite

(See Figures E1-E2 in Appendix 2.)

^{14}C measurements of only the Turffontein and Gerrit Minnebron springs have been obtained in the West Rand dolomite basin. Both these springs have been polluted by effluent from the mining dumps rendering them unsuitable to use the measured chloride concentrations to determine the average recharge. Thus in this case deriving the parameters of the ^{14}C simulations relied on expert hydrological judgement as well as obtaining a good agreement between the simulated and measured bicarbonate concentrations. The results of the ^{14}C simulations appear in Table 6.

Discussion of results (see Table 6)

Table 6. Results of ^{14}C simulations of West Rand dolomitic springs.

	Gerrit Minnebron	Turffontein eye
F**actors Minimum**	**11.7**	**13.5**
Lower threshold (mm)	10	23
Higher threshold (mm)	74.5	68.4
Recharge factor (N)	0.09	0.099
Recharge factor (H)	0.066	0.081
^{14}C factor (N)	0.754	0.864
^{14}C factor (H)	0.502	0.708
Multiples of deep flow	**8.83**	**3.1**
Period 1 – shallow flow	36	36
Period 2 – deep flow	548	500
Start year	1922	1922
Start month	1	1
Months for long term average	946	937
Turnover (years)	**22**	**17.3**
Rainfall weighting (months)	36	78
^{14}C – lower threshold (months)	36	36
Surplus – lower threshold (months)	36	36
Surplus – higher threshold (months)	36	36
^{14}C – higher threshold (months)	36	36
Final lag (months)	**16**	**10**
HCO3 of spring water (mg/l)	181.5	248.4
Measured HCO3 (mg/l)	201	204
Recharge area (km^2)	796	20
Cl spring uncontaminated (mg/l)	7.5	7.5
Recharge coefficient Cl method (CMB)	0.084	0.084
^{14}C simulated recharge coefficient	0.08	0.08

For both springs the lower and higher recharge thresholds as well as the recharge coefficients are comparable and the values are in accordance with those obtained for other springs in a similar dolomitic environment. The ^{14}C factors for the normal and high-rainfall recharge have yielded acceptable bicarbonate concentrations and a recharge area of 796 km^2 for Gerrit Minnebron eye has yielded a good simulation of the available flow records. The higher multiples of deep flow in the case of Gerrit Minnebron eye (8.83) in comparison to 3.1 for Turffontein eye accords with the latter spring having a smaller recharge area and average flow than that of Gerrit Minnebron. The mixing periods of 36 months for the shallow flow contributions of both eyes are comparable to that of other dolomitic springs and their deep flows are integrated over a period of 500 to 548 months.

The ^{14}C simulations of these two springs have been incorporated in Section 8 dealing with the propagation of pollution in dolomitic aquifers.

5.6 Springs of the Ghaap Dolomite (see Figure 10)

5.6.1 Springs in the Kuruman area (see Figures F1-F5 for ^{14}C graphs in Appendix 2)

The largest number of ^{14}C measurements has been obtained for Kuruman A eye with one set of values measured by the CSIR and the other by the Environment Isotope Group (EIG), previously known as the Schonland Research centre of the University of the Witwatersrand. For the smaller springs namely Kuruman B eye, Klein Kono, Groot Kono and Manyeding A, fewer ^{14}C analyses have been carried out. For all of these springs except for Klein Kono eye their flows have been measured but the records are discontinuous at times and the full flow records have been simulated from the MA method (see Figures F in Appendix 2). The ^{14}C modelling of these springs has contributed in a significant way to derive the characteristics of these dolomitic aquifers.

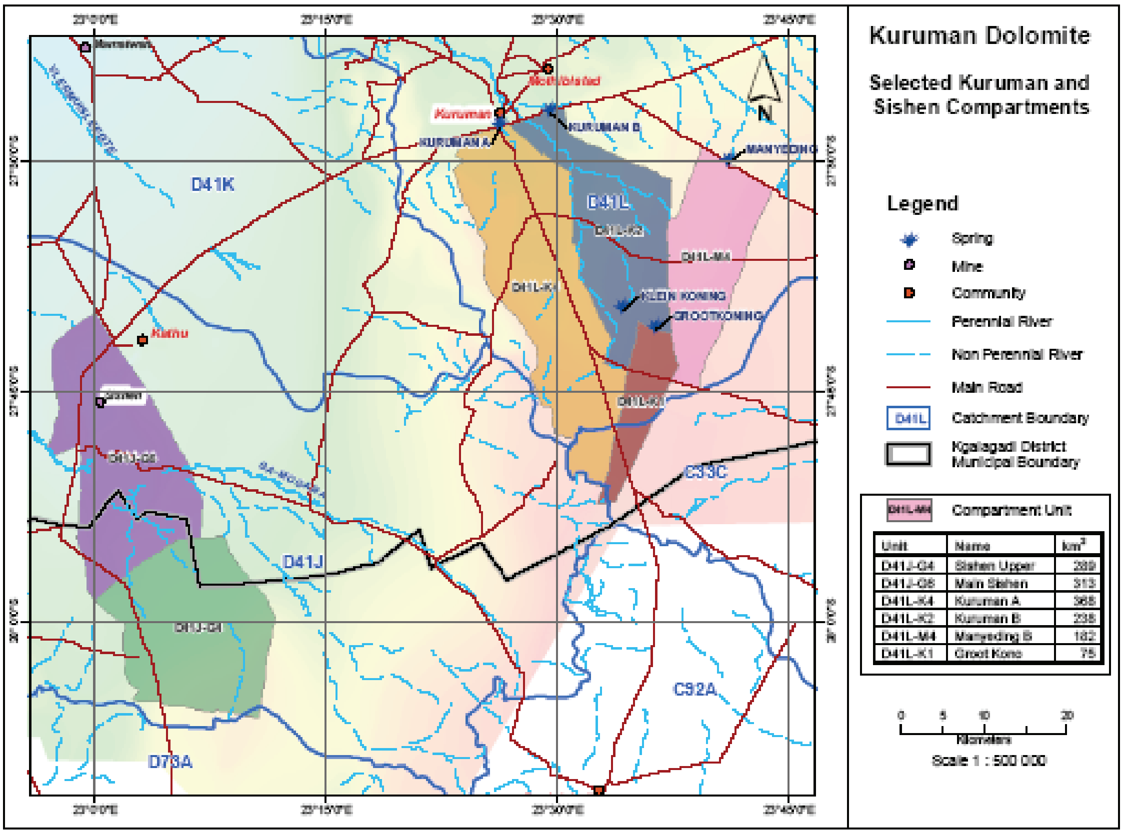


Figure 10. Delineation of compartments in the Kuruman/Sishen dolomitic area sustaining the flows of major springs and abstraction.

^{14}C results

The outcome of the ^{14}C simulations of springs in the Ghaap basin is listed in Table 7 and in Figures F1 to F5 in Appendix 2. The EIG data showed a greater scatter in the case of Kuruman A spring than that of the CSIR but they extend over a longer period; overall the shape of the ^{14}C pulse has been similar.

Table 7. Results of ^{14}C simulations of Kuruman dolomitic springs.

	Kuruman A	Kuruman A	Kuruman B	Manyeding A eye	Groot Kono eye	Klein Kono eye
	EIG data	CSIR data				
Factors Minimum error	**380**	**45**	**27**	**1.5**	**0.7**	**20.2**
Lower threshold (mm)	20	42.3	26.9	14.2	14.4	11.9
Higher threshold (mm)	65	75.1	66	71.9	27.9	50.1
Recharge factor (N)	0.106	0.119	0.084	0.043	0.032	0.052
Recharge factor (H)	0.07	0.088	0.057	0.02	0.02	0.036
^{14}C factor (L)	0.658	0.704	0.822	0.88	0.97	0.99
^{14}C factor (H)	0.551	0.5	0.514	0.61	0.57	0.6
Multiples of deep flow	**2.31**	**2.05**	**1.52**	**0.82**	**1.71**	**2.08**
Lag period 1 (months)	240	300	250	36	1	36
Lag period 2 (months)	597	505	502	288	280	288
Long term average rainfall						
Start year	1915	1922	1922	1922	1922	1922
Start month	1	1	1	1	1	1
Months for long term average	946	946	946	946	946	946
Turnover (years)	**22.4**	**22.4**	**27.3**	**7.4**	**8.6**	**10.9**
Rainfall weighting (months)	60	12	36	36	36	24
^{14}C – lower threshold (months)	1	24	36	36	36	24
Surplus – lower threshold (months)	1	24	36	36	36	24
Surplus – higher threshold (months)	1	24	36	36	36	24
^{14}C – higher threshold (months)	1	24	36	36	36	24
Final lag for ^{14}C simulation	**133**	**98**	**6**	**47**	**66**	**4**
HCO3 simulated (mg/l)	149	149	207	260	258	293
Measured HCO3 (mg/l)	162	162	211	277	256	313
Recharge area (km^2)	286	232	72	106	392	12
Chloride concentration (mg/l)	5.3	5.3	5.1	10.8	11.3	10.6
Cl recharge coefficient	0.085	0.085	0.086	0.042	0.040	0.044
^{14}C recharge coefficient	0.08	0.086	0.075	0.042	0.040	0.06

Manyeding B eye oozes from a large surface pool with substantial vegetation growth around the perimeter, which could increase the natural ^{14}C content of the water. However, the flow is perennial so that there is not much exposure of the outflow to ^{14}C from the vegetation. The chloride concentrations of Manyeding B, Groot Kono and Klein Kono springs are similar indicating that their recharge ranges between 7 to 8 % of the average annual rainfall. The lag time of the Klein Kono eye is smaller than that of the other two eyes but the mixing periods are similar.

The ^{14}C result of the two sets of data of Kuruman A are slightly different insofar that the low-threshold for the CSIR model is higher than that using all the data. The final lag period of 133 months using all the ^{14}C data is larger than the 98 months lag, using only the CSIR measurements. For both sets the recharge derived from the chloride concentration of the spring has been matched. The mixing periods of the shallow and deep waters however are different but the multiple factor for both simulations are comparable.

Kuruman B eye

The ^{14}C results indicate that recharge occurs more rapidly to this smaller recharge area although the parameter values are similar to that of Kuruman A. However, the final lag by which the entire simulated pulse has to be shifted (6 months) is much smaller than that of Kuruman A. These, as well as the higher ^{14}C factor of the normal recharge component, are in accordance with the Kuruman B eye being recharged by a smaller dolomitic aquifer but the turnover time of its storage is still large, indicating inflow from higher laying compartments.

Manyeding B eye (See Figure F3 in Appendix 2)

For this spring flow measurements are available from which the recharge area could be inferred in relation to the recharge derived according to the CMB method.

Groot and Klein Kono springs (see Figures F4-F5 in Appendix 2 and Table 7).

These two springs issue in close proximity and their recharge and flow parameters are consistent and only differ in respect of the ^{14}C factors. The higher ^{14}C -factor for both Kono eyes (0.97 and 0.99) is in accordance with a shallow groundwater system that has a rapid through-flow of recharge. Good correspondence between the measured and simulated values of chloride and bicarbonate in comparison to the measured concentrations provides validation of the reliability of the parameters obtained from the ^{14}C simulations.

The contribution of deeper water of both the Kono eyes and that of Manyeding B eye is similar but the high final lag (66 months) for Groot Kono eye still needs clarification.

Simulation of Klein Kono eye (see Figure F5 in Appendix 2 for ^{14}C simulation).

5.6.2 Sishen dolomite (See Figure 10, Table 9 and Figure G1 in Appendix 2).

The ^{14}C simulations of the Sishen Mine aquifer has been based on data derived from Verhagen et al., 1979. The abstraction quantities in the mining area have been simulated assuming that they represent the rates of flow of a spring.

1) Simulation of the abstraction from the mining area.

Figure 11 shows the good simulation that has been derived from the abstraction rates according to the MA method. For the best result a recharge factor of 2.2 % of the rainfall in excess of a monthly threshold of 15 mm has yielded the same average recharge as has been determined from the CMB method. In this case the high-threshold recharge component turned out to be zero and a component of old water (^{14}C < 30 % mc) is present. The average recharge for the entire period is 0.027 times the long-term average rainfall, because of the weighting factor that is applied to the recharge coefficients, i.e. the ratio of rainfall over the preceding 12 months relative to the long-term average rainfall. This recharge coefficient is also matched according to the CMB method (0.027). From the model the recharge area that is required to maintain the rates of abstraction at the mine, is 280 km^2 compared to a delineated main catchment area of 318 km^2.

2) Recharge simulated from groundwater level fluctuations in the mining area.

The response of the groundwater levels, in the Sishen mining quarry has also been simulated from the relationship between the recharge and the moving average of rainfall of a characteristic period (MA method – see Figure 12). The effect of abstraction on the levels has initially been incorporated in the water balance as an equivalent pumping rate over an area of 280 km^2. The best simulation of the water levels has been obtained for a recharge coefficient of 0.025 that has been weighted by the ratio of the average rainfall over the preceding 24 months to the long-term average rainfall. As the recharge occurs over an area of 280 km^2 and because the transmissivity of the aquifer is high, the impact of the abstraction on the water levels over the entire aquifer is small. This even applies if it is assumed that the effective pumping area is 1 km^2 (Bredenkamp, 2004). For a highly transmissive aquifer, as is the case with the Sishen mining area, the corresponding effective area that controls the groundwater levels in the mining quarry could, however, be larger. The storativity that is derived from the MA simulation (S = 0.05) probably reflects the specific yield of the aquifer in the immediate vicinity of the mining area, i.e. that of the chert-breccia zone. The specific yield of the entire aquifer would be lower and can be calculated if integrated water level fluctuations over the entire aquifer are available.

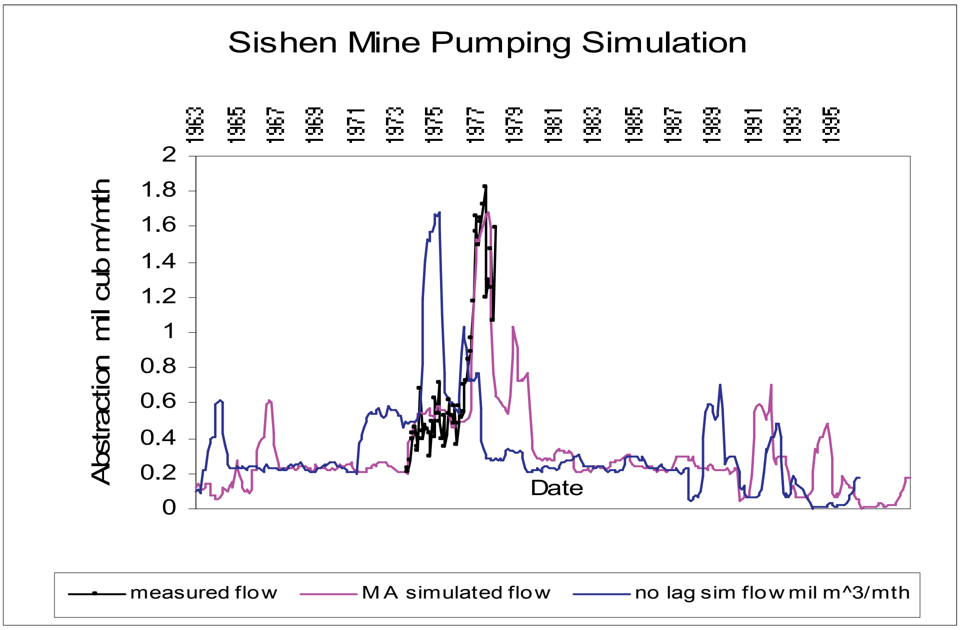


Figure 11. Comparison of the measured rates of abstraction and the simulated values, indicating that the measured abstraction lags the simulated rates by 30 months (see Table 9).

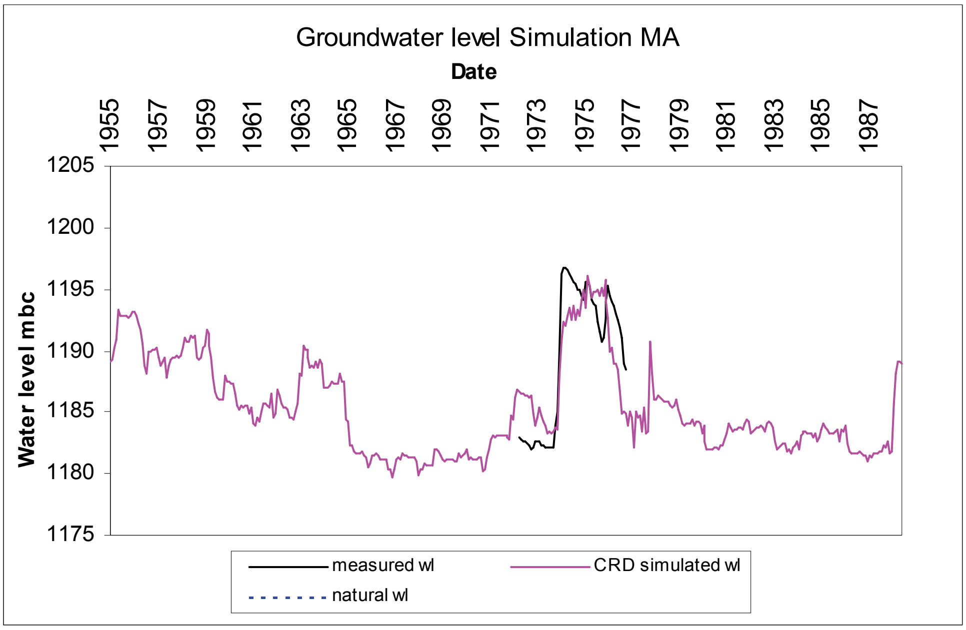


Figure 12. Water level response in the pumping area of the mine incorporating the abstraction over an effective area of 4 km^2. For this simulation the specific yield of the aquifer is 0.052 to obtain the best fit.

The natural response of the aquifer levels could be obtained by inserting zero abstraction in the MA relationship. Similarly the impact of any pumping rate on the groundwater levels could be simulated from the MA relationship, e.g. to obtain the levels that would be required for mining operations to continue normally. The water level response in the quarry area depends on the effective area of abstraction, which in this case appears to be 4 km^2.

Section 6. Simulations using tritium as environmental tracer

6.1 Background

Concurrently with the ^{14}C input from thermonuclear tests, tritium (^3H) has been released into the atmosphere with a similar tracer input-pulse, although its maximum concentrations has been 30 times that of the pre-bomb levels, in comparison to 1.6 times in the case of ^{14}C (see Figure 13). The pre-bomb tritium has increased from about 2 TU (tritium units) to about 60 TU in 1962 and thus provided a distinct signal to the groundwater recharge and its propagation through the aquifer.

The declining input tritium values seen from around 1980 are similar to the input pulses of the ^{14}C and tritium, indicating that the removal of tritium by rainfall from the atmosphere has been slightly faster than that of the ^{14}C.

Similar to ^{14}C the reappearance of the tritium pulse in the spring outflow has been simulated. However, in view of the decay of tritium according to its half-life of 12.3 years, the tritium input values have to be corrected for decay for each of the simulating months whilst incorporating the final lag as well. The decay corrections in the tritium simulation program still allowed interactive manipulation of the parameters (see model in Appendix 4). Deriving the best simulations have not included the uncertainty in the tritium measurements, which for low concentrations is of the same magnitude as the low measured concentrations.

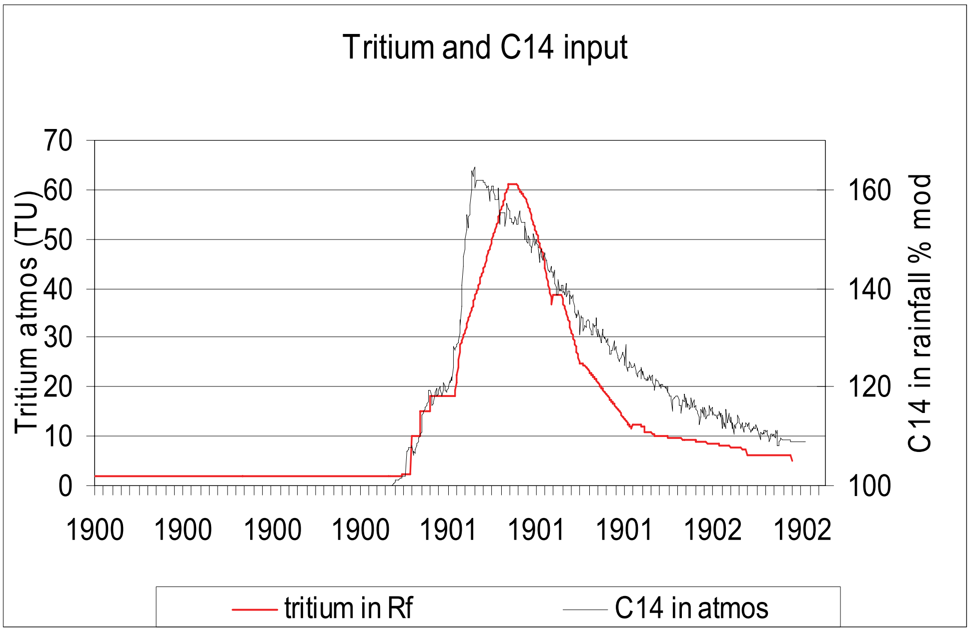


Figure 13. Comparison of the input concentrations of ^{14}C and tritium in the rainfall.

The tritium simulations have not been optimised on their own but have been applied using the same recharge parameters derived from the ^{14}C model, only adjusting the final lag and the multiples of deep flow. The final lag period for the tritium simulations proved to be reasonably the same as that derived from the ^{14}C simulations. However, a distinctly larger contribution of deep flow has been required to achieve the best simulation for tritium. A larger contribution of deep flow in comparison to the ^{14}C simulation has also been required in previous simulations by Bredenkamp et al. (1995) for Kuruman A eye. Explanations of the larger deep-flow component are presented in Section 6.2.

6.2 Tritium simulations

Kuruman springs (See Figure 10)

The best series of tritium measurements are those for Kuruman A and B as well as for Manyeding B spring. For several springs only two to three tritium determinations have been obtained. Tritium measurements have been carried out by both the CSIR as well as EIG (previously Schonland Institute) and it is assumed that both sets of analyses are reliable. The outcome of the simulation for Kuruman A spring is shown in Figure H1 in Appendix 5, using the tritium measurements of both the CSIR and EIG laboratories. The tritium simulations for Kuruman B, Manyeding, Groot Kono and Klein Kono eyes are shown in Figures H2-H5 in Appendix 5, and the recharge and flow parameters are listed in Table 8.

Interpretation of tritium simulations

Good matches have been obtained for Kuruman A using the same set of parameter values of the ^{14}C simulations (see Table 8), however, a much larger component of deep water is required in the tritium model to achieve a good fit. The simulated tritium and ^{14}C pulses of Kuruman A (CSIR data) are almost identical if a deep flow component of 6.5 is used for the tritium, compared to 2.3 for the ^{14}C simulation (see Table 8). This is contradictory as there are more hydrogen atoms in the unsaturated zone with which the tritium exchanges during its movement as part of the recharge. A substantially greater dilution of the tritium tracer therefore must have occurred by the time it reaches the saturated aquifer, which is not incorporated in the ^{14}C model. The dilution process is similar to the differential diffusion and adsorption a tracer undergoes in an aquifer. Shapiro (2001) has obtained a similar discrepancy of the response of tritium and CFC being used as tracers on a scale of several kilometres.

Table 8. Summary of the recharge parameters according to tritium simulations.

	Kuruman A CSIR data	Kuruman A plus Wits	Kuruman B	Manyeding Eye	Groot Kono eye	Klein Kono eye
Minimum error	**2.90**	**30.39**	**1.38**	**1.59**	**0.04**	**8.09**
Lower threshold (mm)	40.6	40.6	26.9	14.2	14.4	12.9
Higher threshold (mm)	77.3	75.5	66	71.9	27.9	51.7
Recharge factor (N)	0.11	0.11	0.09	0.04	0.030	0.031
Recharge factor (H)	0.075	0.075	0.061	0.02	0.018	0.022
Tritium factor (N)	1	1	1	1	1	1
Tritium factor (H)	1	1	1	1	1	1
Multiple of deep flow (tritium)	**6.5**	**16**	**14**	**11**	**7**	**5**
Multiple of deep flow for ^{14}C	**2.31**	**2.05**	**1.52**	**0.82**	**1.71**	**2.08**
Lag months period 1	36	36	250	36	30	30
Lag period 2	505	505	502	288	288	288
Long term average rainfall						
Start year	1922	1922	1922	1922	1922	1922
Start month	1	1	1	1	1	1
Months for long term average	946	946	946	946	946	946
No. of months included in averages of:						
Rainfall weighting (months)	12	12	36	36	36	36
Tritium – lower threshold (months)	24	24	36	36	36	36
Surplus – lower threshold (months)	24	24	36	36	36	36
Surplus – higher threshold (months)	24	24	36	36	36	36
Tritium – higher threshold (months)	24	24	36	36	36	36
Final lag for tritium (months)	142	84	60	48	13	13
Final lag for ^{14}C (months)	133	97	6	47	66	4
Simulated HCO3 of spring water	149	149	207	263	258	282
Measured HCO3 (mg/l)	162	162	211	277	256	313
Recharge area (km^2)	36	36	36	36	36	36
Cl recharge coefficient	0.085	0.085	0.10	0.042	0.040	0.06
Tritium recharge coefficient	0.08	0.086	0.10	0.042	0.040	0.06

Section 7. Use of CFC as environmental tracer

7.1 Previous studies

Three CFC molecules (CFC11, CFC12 and CFC13) have been produced for the refrigeration industry and have been released into the atmosphere since about 1950 by this industry and are being used as an environmental tracer. Because of the stability of the molecules their concentrations in the atmosphere have steadily increased over the years and through recharge have contaminated the groundwater reservoirs. The concentrations of CFC in the groundwater emerging from springs in comparison to the input from the atmosphere could be used to check the reliability of the ^{14}C model and its response in comparison to using tritium as a tracer could be examined.

Talma and Weaver (2003) investigated the application of the CFC as environmental tracer in groundwater in South Africa. This revealed the presence of CFC in both shallow groundwater systems as well as in the dolomitic springs with a large turnover time. Some of the spring samples however have been contaminated during the sampling or processing of the CFC. No quantitative relationship between the CFC input (as part of the recharge) and that of the outflow from a spring could be inferred. Also in view that only single CFC measurements have been obtained, the time-variant response of the CFC could not be examined. However, from the CFC simulations of the dolomitic springs applying the recharge parameters of the ^{14}C simulations, the deep flow contribution in relation to that derived for ^{14}C and tritium could be compared.

7.2 CFC results

The CFC simulations of some dolomitic springs using the parameter values of the ^{14}C simulations are shown in Appendix 6 (Figures I). The parameter values are the same as for the ^{14}C modelling and the contributions of deep flow are summarized in Table 9.

It turned out that the multiples of the deep flow for the CFC model of Maloneys eye are smaller than that derived from the ^{14}C simulations. This indicated that the CFC tracer conforms well to the ^{14}C model. In the case of Doornplaat the multiples of the deep flow is about half those of the ^{14}C values, this is ascribed to a much faster input of CFC from recharge from the Malmani River. The input of CFC is probably effected at a greater depth in the aquifer, as it occurs directly at the interface between the atmosphere and the saturated levels of the groundwater. Hence dilution of the CFC only occurs from the time flow commences in the saturated zone and therefore in the unsaturated zone it is less than that of tritium and ^{14}C. Some losses due to instability of the CFC molecule cannot be ruled out.

In view of the apparent contamination of the Grootfontein (Molopo) sample the effect of a thicker overburden of soil overlying the aquifer, in comparison to a shallow overburden as in the case of Maloneys eye, could not be clarified. The higher dilution that is required by the deep flow component in the case of tritium however appears to be greater in aquifers where there is a thick overburden of unsaturated aquifer. The dilution required from the deep flow component in the case of ^{14}C and CFC tracers is not as much as for the tritium.

Table 9. Comparison of chloride recharge coefficients and CFC and ^{14}C multiples.

Spring		Multiple of deep flow	Cl of rainfall mg/l	Cl of spring mg/l	Cl Recharge Coefficient	^{14}C Recharge Coefficient
Buffelshoek eye	^{14}C	3.18	0.56	7.3	0.077	0.077
Doornplaat	^{14}C CFC	3.96 2.54	0.56	5.86	0.096	0.096
Gerrit Minnebron	^{14}C CFC	15.2 0	0.63	5.8	0.109	0.109
Grootfontein Molopo	^{14}C Tritium CFC	4.12 6 0.33	0.56	4.6	0.122	0.122
Kuruman A eye	^{14}C Tritium	2.3 6.5	0.47	5.3	0.085	0.085
Kuruman B	^{14}C Tritium	1.52 14	0.47	5	0.094	0.094
Manyeding	^{14}C Tritium	0.82 7	0.47	10.8	0.044	0.044
Marico Grootfontein	^{14}C	1.14	0.63	2.4	0.263	0.263
Molopo eye	^{14}C Tritium	7.62 11.5	0.56	4.7	0.119	0.119
Olievendraai eye	^{14}C CFC	1.08 2.38	0.56	7.7	0.073	0.073
Paardevlei	^{14}C	2.03	0.56	7.3	0.077	0.077
Pretoria Erasmus eye	^{14}C	17.18	0.65	4.8	0.135	0.135
Pretoria Grootfontein	^{14}C	11.98	0.65	4.8	0.135	0.135
Renosterfontein	^{14}C CFC	2.59 0.95	0.63	5.9	0.107	0.107
Rietgat Molopo	^{14}C	0	0.56		0.125	0.123
Schoonspruit eye	^{14}C Tritium	1.5 10.5	0.63	6.3	0.100	0.100
Turffontein	^{14}C	2.01	0.63	7.5	0.084	0.084
Upper Mooi River	^{14}C CFC	10.86 4.61	0.63	6	0.105	0.105
Vergenoegd eye	^{14}C	2.53	0.56	5.8	0.097	0.097
Groot Kono eye	^{14}C Tritium	1.5 6.5	0.4	11.3	0.080	0.075
Klein Kono eye	^{14}C Tritium	1.9 4.71	0.4	11.3	0.060	0.06
Pretoria Fount Upper	^{14}C	2.62	0.65			
Pretoria Sterkfontein	^{14}C	2.23	0.65	6.04	0.108	0.108
Doornfontein eye	^{14}C	1.6	0.56	7.68	0.073	0.073
Lichtenburg	^{14}C	1.49	0.56		0.125	0.125
Stinkhoutboom	^{14}C	2.1	0.56	5.6	0.100	0.100

Possible reasons why contributions of the deep-flow is different for the various tracers, are presented below:

- There is a distinct difference between the flow paths and propagation of ^{14}C and of tritium, e.g. ^{14}C is essentially introduced at greater depths at the root zone in the unsaturated layers, whereas tritium propagating though the entire soil zone is diluted by a much larger reservoir of hydrogen atoms with low tritium in the unsaturated flow regime.
- In the model only upon entering the saturated aquifer the admixing of the deep and shallow flows occurs. Thus an initial dilution of the tritium has to occur in the unsaturated regime to obtain the measured tritium concentrations.
- The explanation in the case of CFC tracers is that its introduction occurs more directly from the interface between the air and the saturated groundwater levels in the aquifer. As this effects a direct CFC input into the dynamic flow zone, the dilution of CFC reaching the saturated aquifer in comparison to ^{14}C is smaller.

There could also be some losses by degradation of the CFC molecules, which would then require a smaller deep-flow component than for ^{14}C. The multiples of deep flow appear to be highest for the tritium, smaller in the case of the ^{14}C and the lowest for the CFC simulations.

The differences in the deep flow contribution of the different tracers according to the present model, therefore provides a quantitative indication of the relative magnitude of the unsaturated zone's recharge in relation to that of the total storage in the aquifer. The multiples of the deep flow component that is required in the case of tritium, therefore reflects the turnover time (dilution) of water in the saturated and unsaturated zones, whereas in the case of ^{14}C and CFC the multiple of deep flow is largely that of the saturated zone.

From the results it appears that the ^{14}C provides a better mixing model of water transport in the saturated aquifer, because of the uptake of ^{14}C in the root zone, whilst for CFC a smaller dilution by the deep flow component is required because the uptake of CFC occurs at the interface between the unsaturated and saturated transition of the aquifer. There could, however, be losses of CFC due to instability of the CFC molecules. This interpretation has a significant effect on the assessment of the propagation of pollutants in a dolomitic aquifer as the characteristics of the pollutant as well as that of the dual recharge process has to be incorporated.

Section 8. Application of ^{14}C model to simulate groundwater quality

The use of the ^{14}C simulation model to determine the variability of its natural chemical ingredients, e.g. chloride and bicarbonate, for the estimation of recharge, has been another objective of the present project.

8.1 General

The chemical pollution of dolomitic groundwater has been the subject of many studies (Verhoef and Bredenkamp, 1981; Fleisher, 1981; Scott, 1994; Simonic, 1993), the pollution status transport and hydrodynamic dispersion of contaminants and their emergence at springs. As has been indicated certain chemical components of the groundwater, e.g. chloride concentrations and bicarbonate, could be used to derive the average recharge (see Section 8.4.1).

Dolomitic springs are fed from ecologically sensitive systems that require reliable techniques to assess the status and risks of pollution and the effectiveness of remedial measures for large systems.

Although theoretical flow models could simulate the propagation and dispersion of a contaminant, it is difficult to check their reliability, especially in large dolomitic aquifers of which the circulation of the deep water is not known, as can be done with environmental ^{14}C tracers.

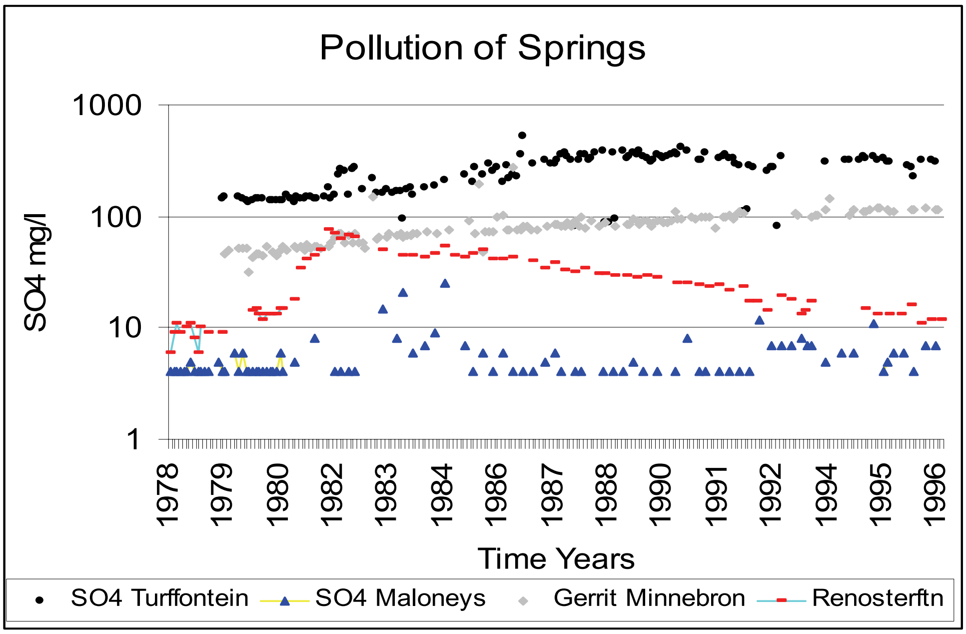


Figure 14. Sulphate concentrations of dolomitic springs indicating different degrees of pollution relative to the uncontaminated Maloneys eye.

Springs in the West Rand dolomitic aquifers (Figure 1) have been polluted by the gold mines, e.g. in the case of Turffontein and Gerrit Minnebron. In the case of Renosterfontein pollution of the aquifer has occurred but has already been dissipated (see Figure 14). For Maloneys eye no pollution has yet occurred. In cases of accidental spillage a reliable evaluation of the environmental impact and the effectiveness of clean-up measures is needed to avert unnecessary alarm or to take action accordingly.

Few studies involving the modelling of contaminant flow on a regional scale has been successfully carried out in the RSA, but a reasonable simulation (by MODFLOW) has been obtained of the Gemsbokfontein dolomitic compartment (Simonic, 1993).

Pollution studies usually implement distributed small-scale models to simulate the mass transport of the contaminants through the aquifer, which are often based on a two-dimensional model of the aquifer incorporating assigned transmissivity, storage and recharge characteristics of the groundwater system.

For large aquifers it is difficult to assess the reliability of such theoretical models in view of

- the variability of the recharge;
- the heterogeneity of the aquifer transmissivity and
- the scale of the problem and lack of data on the input that caused the contamination. Insufficient knowledge and understanding of what the impacts on large groundwater systems are, also limits protection of these resources and leads to failure of the prosecution of polluters.

Thus the present study has focussed on the sulphate pollution of Turffontein, and Renosterfontein

- using the ^{14}C flow model to assess the nature/impact of point-source pollution or diffused contamination on a dolomitic aquifer;
- establishing the status of pollution of these aquifers and deriving the probable origin and dates when the pollution had started;
- simulating the natural concentrations of the groundwater;
- assessing the possible long-term impact of remedial measures on a typical dolomitic aquifer based on a simulation of Turffontein eye.

8.2 Water quality variations of dolomitic springs

Turffontein eye

All indications are that the pollution of this spring has occurred from effluent spilled from the tailings dams of the gold mines as is evidenced by the high incidence of sulphate and the corresponding response between the sulphate and chloride shown in Figure 15.

It is clear from Figure 15 that the pollution had commenced about 1959, i.e. when the mining had started, and had remained constant up to about 1977, whence it increased and remained effectively constant from 1988 until 2001.

Figure 15 indicates the simulated decontamination response if the influx of the pollution had been stopped completely in 2001, and assumes a recurrence of the rainfall sequence over the period 1940 to 2001 for the extended period up to 2064. This indicates that the pollution pulse would only be reduced to 100 mg/l after 64 years. Also in this case the pre-pollution chloride concentrations of the spring are inferred to have been 5 mg/l. This value has been used in establishing the recharge according to the bicarbonate concentrations of the springs.

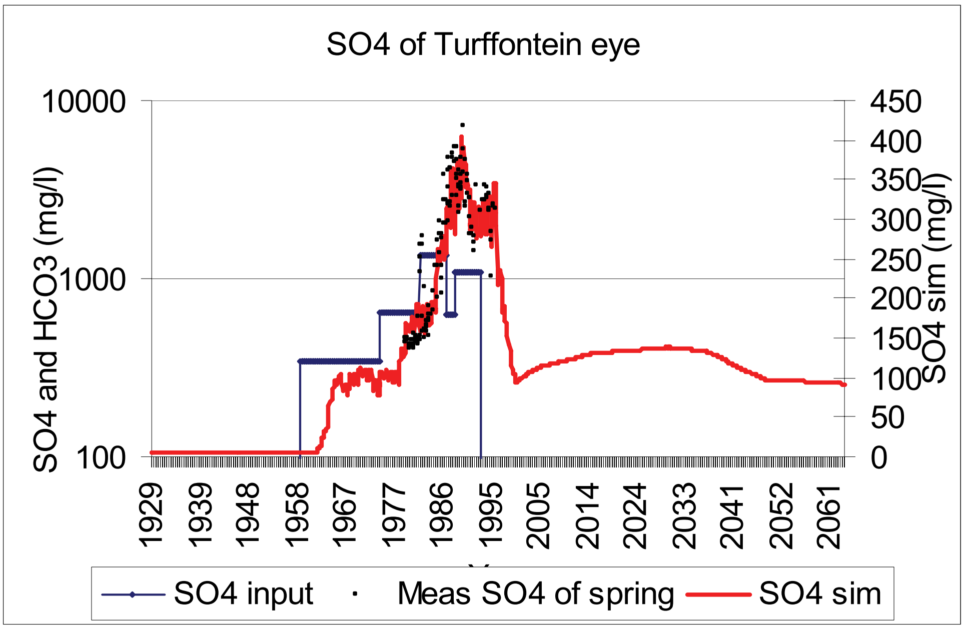


Figure 15. Simulated pollution of Turffontein spring vs the measured concentrations.

The contamination of Turffontein spring is an example of pollution that has occurred over a long period (Figure 15), compared to Figure 16 indicating pollution from a short-term spillage in the Renosterfontein aquifer. For Gerrit Minnebron eye, lying further downstream of Turffontein eye, the pollution levels are much lower because of dilution of the pulse from Turffontein eye by recharge occurring in the lower Gerrit Minnebron compartments.

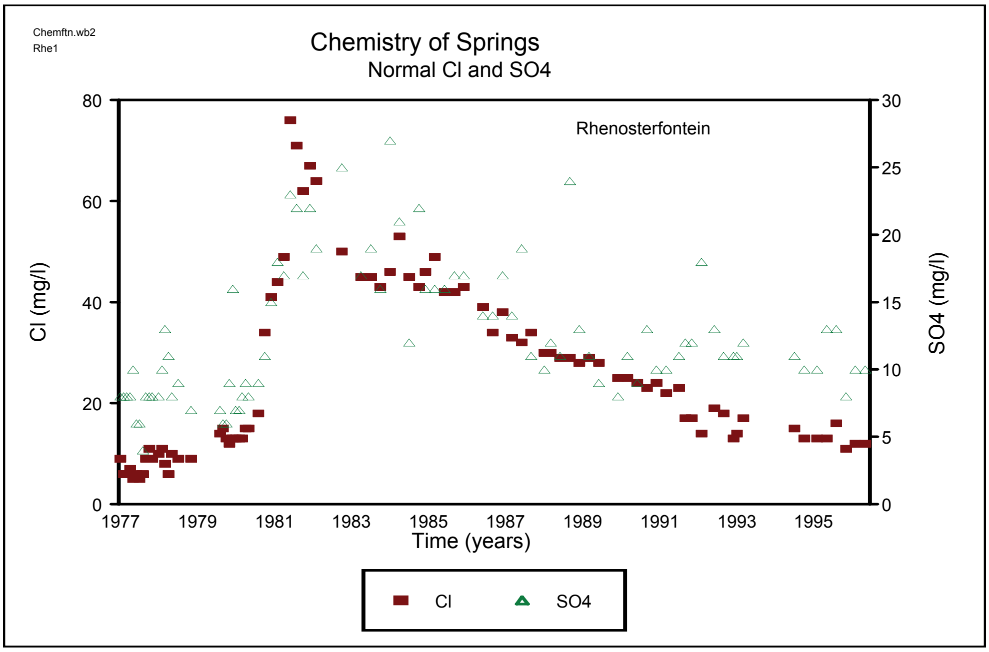


Figure 16. Pollution of Renosterfontein eye according to the sulphate and chloride concentrations of the water, which responded similarly.

Determining the input, flow/transport of contamination

The input and flow of the pollutant through these aquifer systems have been calibrated from the appearance of the environmental ^{14}C input and the recharge controls derived from the ^{14}C model and the flow/mixing relationships. The Excel model (and Haili, 2006) is to provide further insight into the diffusion process as well as to confirm the ^{14}C modelling results.

Renosterfontein

The simulation of the breakthrough curve of the pollution in the spring outflow, according to the transport mechanism in the ^{14}C modelling, has therefore been attempted. Although based on only a few ^{14}C measurements a good simulation has been obtained of the recharge components (see Figure C1 in Appendix 2). By inverse modelling the input-pollution has been simulated (see Figure 17). The pollution has been introduced in the model as if it is introduced over the entire aquifer, although it has probably been injected as a point source. Thus Figure 17 represents a simplified model of the contaminant transport and the input concentrations would have to be adjusted in relation to the actual recharge area to obtain the real input concentrations.

According to Figure 17 the pollution had occurred in 1974, which had been the start of the high rainfall sequence and recharge period that lasted up to 1977. The highest contamination effect has been reached in 1979 (70 mg/l), whereupon it reduced to about 10 mg/l by 1992. It appears highly likely that substantial leakage from a tailings dam could have caused the pollution.

As the natural chloride concentrations of the spring have been increased by the pollution, the CMB method could not be used to determine the average recharge. However, according to the simulated model, the input concentrations of chloride prior to the start of the pollution could be inferred and appeared to have been about 5 mg/l. According to the CMB method this yields an average recharge coefficient of 8.4 %, which can be used as a reference recharge in the ^{14}C model and in relation to the bicarbonate concentrations.

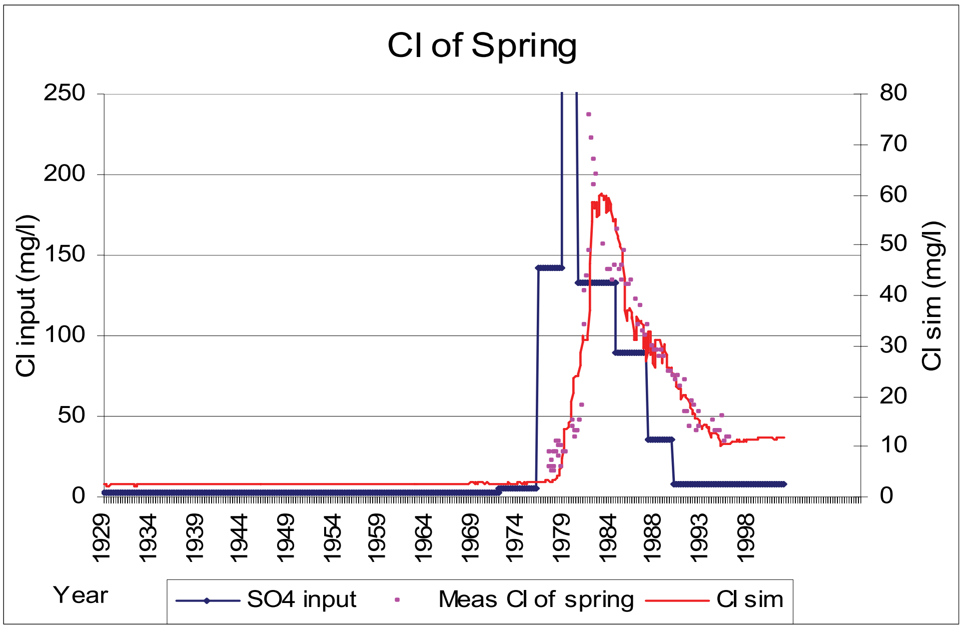


Figure 17. Simulated chloride concentrations versus observed values and the reconstructed input concentrations for Renosterfontein.

8.3 Natural variation of chloride concentrations of dolomitic springs

The natural variations of chloride concentrations of springs have been simulated according to the parameters obtained from the ^{14}C models, controlling the recharge. As there is no difference between the input-chloride concentrations of the normal and direct recharge components, the ^{14}C recharge factors are both assigned a value of 1. The simulated recharge values could thus be used to derive the chloride concentrations according to the inverse relationship of the CMB method.

8.4 Bicarbonate concentrations

8.4.1 Background

Rainfall is the main driving force of recharge but the thickness and characteristics of the overburden of these aquifers control the rate of infiltration to the groundwater, e.g. the soil cover supporting the growth of vegetation loses much of its water by evaporation and transpiration. In the drier areas calcrete deposits often overlay the aquifer underneath and these deposits seem to have a significant effect on the propagation of ^{14}C and tritium to the saturated aquifer at depth (see Rietgat simulation of ^{14}C).

In the present ^{14}C-recharge model the dissolution of bicarbonate is different for the bi-modal recharge components, as it is controlled by the partial pressure of CO_2 in the water.

- The highest concentrations of bicarbonate occur from dissolution of carbonate in the root zone of the vegetation where high partial pressures of CO_2 are generated. This predominantly applies to diffused recharge occurring through the soil zone.
- For the recharge that essentially bypasses the soil zone the dissolution of bicarbonate is limited by the partial pressure of CO_2 that is equal to that of the atmosphere. Consequently in a dolomitic aquifer with diverse surface cover, the bicarbonate concentrations of the groundwater should provide a measure of the bi-modal recharge that occurs. This has been noticed by Bredenkamp (2000) and has been the conceptual basis of the first successful simulation of the ^{14}C of springs (Bredenkamp and Van Wyk, 2005). The large variability of surface features occurring within a dolomitic basin as well as that occurring over areas of different climate, therefore provides a unique opportunity to either prove or disprove that the bicarbonate concentrations of the dolomitic aquifers could be used to derive the recharge of these aquifers. This then could also provide the link to establish the ^{14}C simulation model as an independent method for obtaining reliable quantitative estimates of recharge and of the controlling parameters. Although the variability of recharge (based on its bicarbonate content) over the area is probably large, the bicarbonate of the spring reveals the recharge averaged over time and space, which is less variable.

One of the objectives of the present study therefore has been to use the bicarbonate concentrations for quantitative estimations of recharge in dolomitic aquifers. From the bicarbonate concentrations compared to reliable estimates of recharge, which has been obtained from the chloride concentrations of the spring water, a relationship between the recharge and bicarbonate has been obtained to provide a provisional estimate of the average recharge of dolomitic aquifers.

8.4.2 Simulation of bicarbonate concentrations of dolomitic springs as a means to obtain quantitative estimates of groundwater recharge

The model of the ^{14}C of dolomitic springs has been extended to also simulate the bicarbonate concentrations of the spring water based on the premise that there are two components of recharge.

The relationship in the model is based on a linear interpolation between the two extremes in the bicarbonate dissolution-equilibrium shown in Figure 18. This indicates:

- A maximum concentration of 280 mg/l of bicarbonate that is attained during slow movement of recharge through the unsaturated zone, allowing sufficient contact with high partial pressures of CO_2 in the root zone of plants to reach the maximum bicarbonate concentration. This corresponds to a ^{14}C factor of 0.9 being used in the model.
- A minimum concentration of 51 mg/l, corresponding to a ^{14}C factor of 0.5 that applies if recharge occurs directly to the saturated zone where the dissolution of carbonate is limited because the CO_2 partial pressure of the recharging water is only that of the atmosphere.
- Depending on the relative proportions of direct and normal recharge the bicarbonate concentrations of the water emanating from a spring will vary between these extreme values.

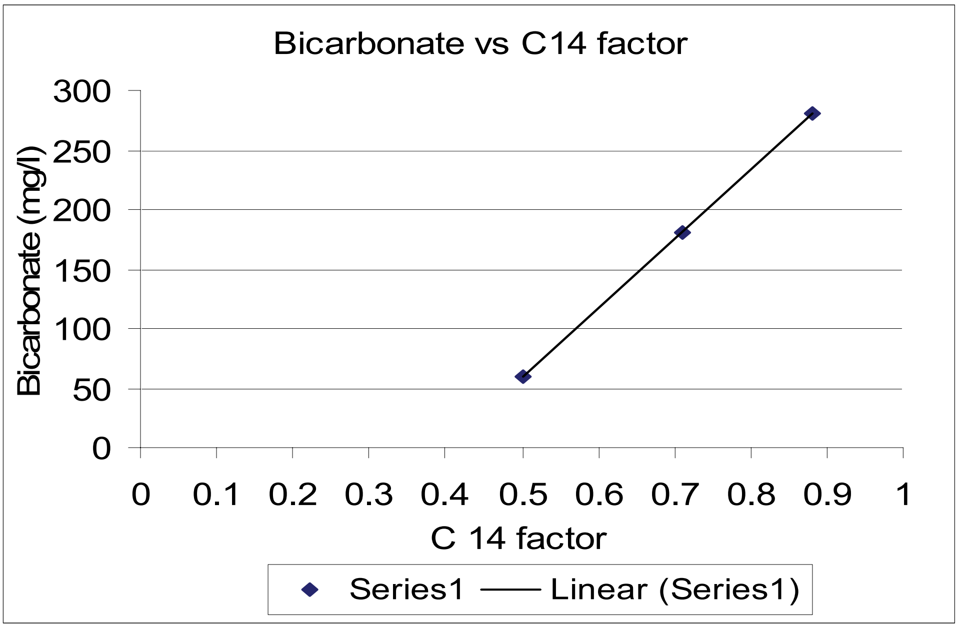


Figure 18. Relationship between the bicarbonate concentrations and the ^{14}C factor used in the simulation model to derive the bicarbonate concentrations.

Obtaining good simulations of both the chloride and bicarbonate concentrations by means of the ^{14}C model would therefore provide an additional check on the reliability of the ^{14}C model and of the recharge controls derived from it. Any significant discrepancies would indicate that the groundwater system does not react according to the conceptual model, indicating a need to look at an alternative source of the recharge as has been indicated for Pretoria Grootfontein, Maloneys, Renosterfontein eyes and Sishen.

The good comparison between the simulated and measured concentrations of bicarbonate proves that the derivation of the bicarbonate concentrations from the ^{14}C model has been reliable (see Figure 19).

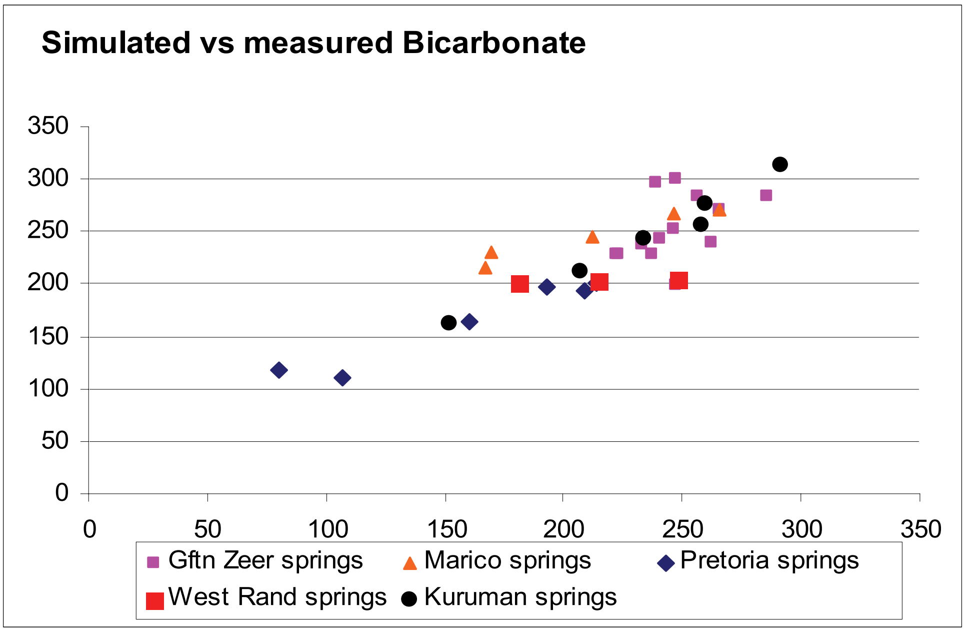


Figure 19. A plot of the simulated and measured bicarbonate concentrations of the various dolomitic springs, indicating a linear relationship.

Thus, if the chloride-estimated recharge (based on the CMB method) also corresponds to the bicarbonate concentrations of the springs, it would indicate that the bicarbonate concentrations could be used to obtain a first quantitative estimation of the recharge of dolomitic aquifers. Figure 20 indicates a linear relationship of declining recharge as the bicarbonate concentrations increase. The correlation coefficient indicates that it would be reasonably reliable to derive the recharge from the bicarbonate concentrations. The spread of some of the points are quite large and the correlation coefficients of the linear relationships are not very high (see Figure 20), however, the regression equation could still be used to derive the average recharge with a reliability of 56 %. The recharge is inversely related to the bicarbonate concentrations as have been postulated. In cases where the springs have been contaminated, e.g. high chloride but normal bicarbonate, the relationship shown in Figure 20 would provide a better estimate of the average recharge than the CMB method, and it should always be used as a check on the CMB estimates. As indicated in Section 8.4.3, the natural chloride of the springs could vary because of variations of the recharge. The bicarbonate concentrations would remain essentially the same in cases where only chemical pollution of the aquifers has occurred. A much more in-depth study of the natural variability of the chloride and bicarbonate of springs is required. Further refinement of the chloride concentrations of the rainfall is needed to improve the correlation coefficient shown in Figure 20, which at present explains only 56 % of the variance.

The variability of the chloride concentrations of a spring could be simulated according to the monthly recharge that has been obtained from the ^{14}C model and the CMB relationship, i.e. the chloride concentration of rainfall to that of the groundwater. It is assumed that the rainfall has a chloride concentration of 1 mg/l. The variability of the simulated chloride in comparison to the measured concentrations of Buffelshoek eye is plotted in Figure 21 and similarly Figure 22 shows the variability of bicarbonate. This shows that the apparent outliers of the measured chloride correspond to the simulated concentrations. It therefore remains a problem even to validate the CMB-recharge estimates, because of the natural fluctuating chloride concentrations of the springs that are used to derive a reference recharge value (see Figure 21).

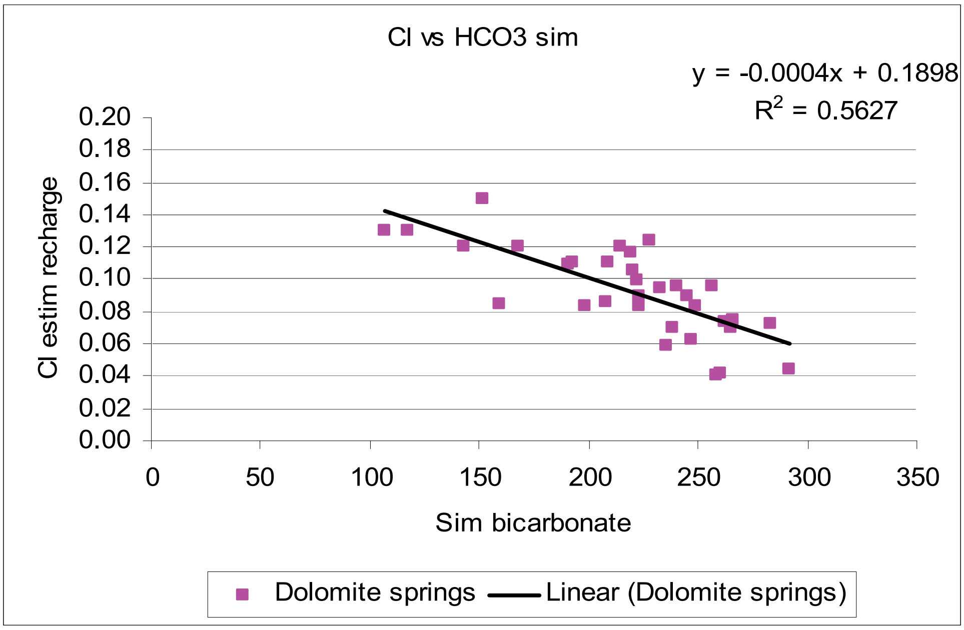


Figure 20. Relationship between the bicarbonate concentrations of the different dolomitic springs and the average recharge coefficients derived from the chloride method.

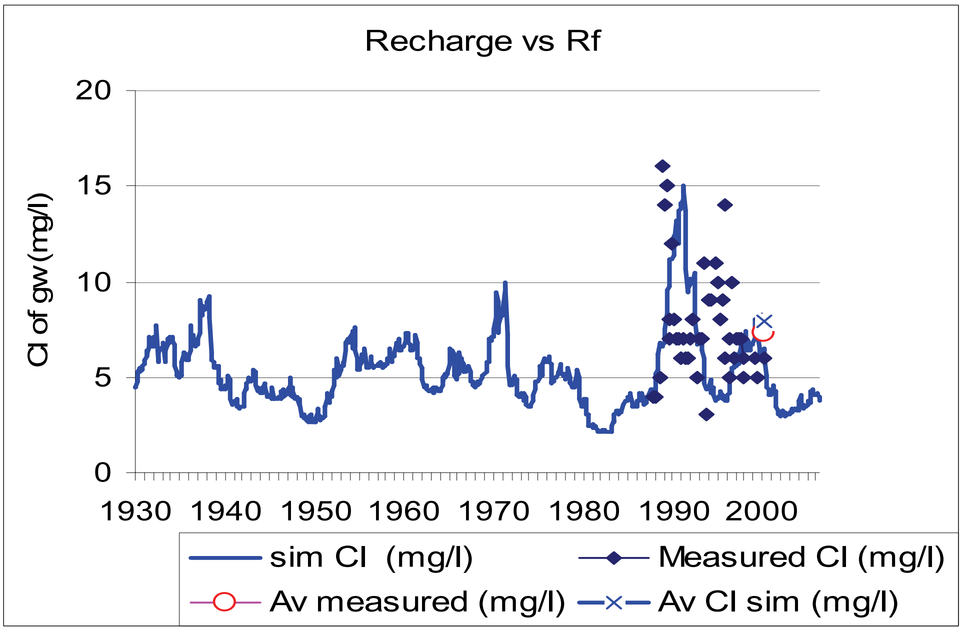


Figure 21. Fluctuations of the chloride concentrations of Buffelshoek eye simulated according to the recharge parameters obtained from the best ^{14}C model based on the average rainfall over 36 months.

The simulated chloride values shown in Figure 21 do not incorporate the deep flow that has been derived from the ^{14}C model but it reflects that of the average recharge that has occurred over 48 months, which effectively incorporates the deeper flow, and accounts for all the rain precipitated on the recharge area and not only the rainfall in excess of the threshold values.

Similarly the bicarbonate concentrations of Buffelshoek eye derived from the ^{14}C model could be compared to the measured values. Again these have been obtained from the average over 36 months and do not incorporate the deep flow component.

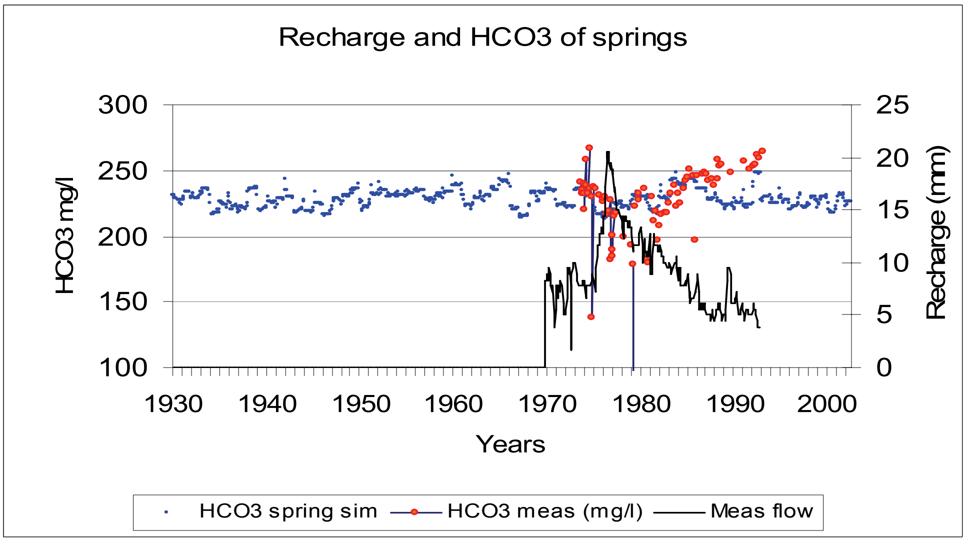


Figure 22. Variations of bicarbonate concentrations of Buffelshoek eye comparing the simulated and measured values in relation to the recharge inferred from the spring flow.

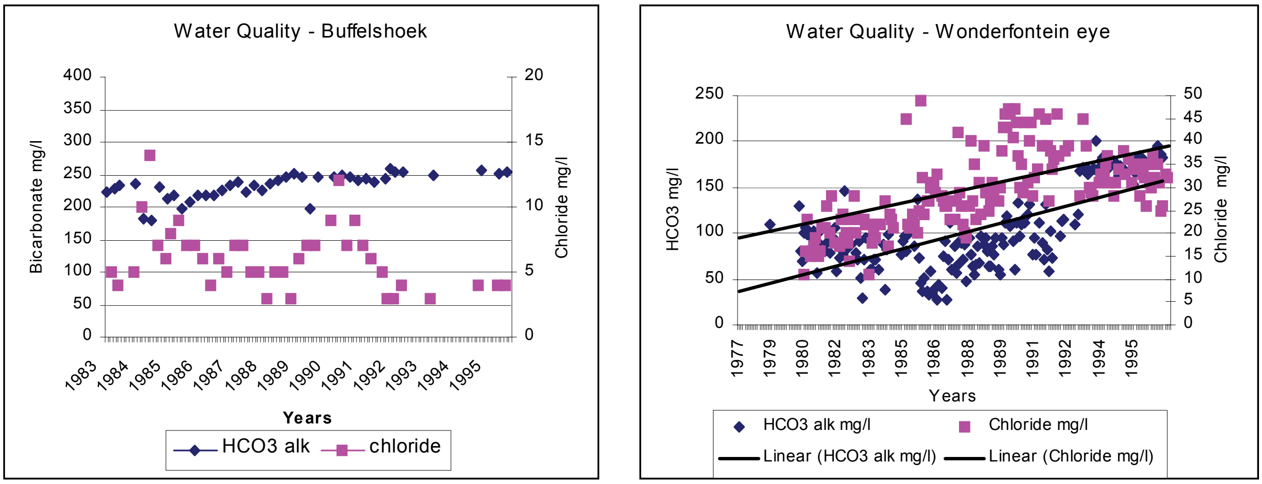


Figure 23. Graph showing the variations of bicarbonate and chloride concentrations of Buffelshoek and Wonderfontein springs. The rising trend of the latter spring is an indication of increased agricultural activity.

In the case of Buffelshoek eye the very low concentrations of bicarbonate shown in Figure 22 are outliers, as the measured high spring flows during these periods include surface runoff, which has low bicarbonate concentrations. The more natural fluctuations of the bicarbonate of the spring water due to wet and dry periods are also shown in Figure 22, which indicates that there is reasonable agreement between the measured and simulated values, although from 1988 the measured bicarbonate values have been higher than the simulated ones. In the case of a rising trend in the bicarbonate concentrations, as is indicated for Wonderfontein Spring (Figure 23), it possibly could be attributed to increased agricultural activity, i.e. the impact of irrigation expansion that has disturbed the natural bicarbonate and chloride concentrations.

8.4.3 Deriving the chloride concentration of the rainfall from an analysis of the flow and the water quality of the dolomitic springs.

As have been indicated in Section 2.2 the most independent and simplest method of estimating the groundwater recharge, especially of dolomitic aquifers, is to derive the effective recharge coefficient from the ratio of the chloride concentration of the rainfall relative to that of the groundwater (CMB method). The reliability of this method depends critically on the following:

- Reliable determination of the very low chloride concentration of the rainfall.
- The chloride concentrations of the spring representing the outcome of the hydrological processes and that they have not been increased by pollution or by chloride leached from the aquifer matrix.

The measurement of the chloride concentration of the rainfall is uncertain, not only because of its low concentration but also because it varies inversely in relation to the amount of the sampled rainfall (Gieske, 1992) according to measurements at Lobatse in Botswana (see Figure 24). Furthermore the rainfall contains a dry-chloride component (from the deposition of dust during the rainless periods). This would increase the chloride that is supposed to be derived from the sampled rain, which complicates deriving the real concentration of the rainfall chloride that characterizes the recharge. Although the chloride of the spring waters contains an uncertainty due to analytical errors, these errors are smaller than the potential errors in the measurement of the low concentrations of rainfall chloride.

It is evident that by extrapolation, a concentration 2.85 mg/l for zero rainfall should represent the dry chloride component that decreases for higher rainfalls.

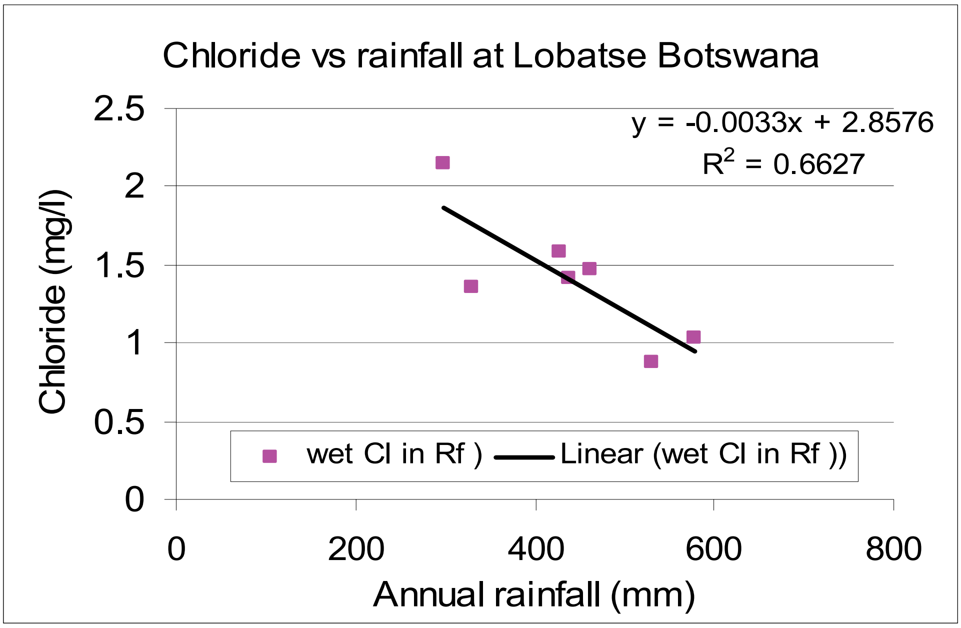


Figure 24. Chloride concentrations in relation to the annual rainfall indicating declining values as the sampled rainfall increases and the dry component decreases (one outlier point has been omitted for the relationship to be more in agreement with preliminary results indicating lower chloride at high rainfalls in the RSA dolomitic areas).

New method to determine the chloride concentration of the rainfall

A new method of determining the chloride concentration of the rain is put forward by deriving it from the outcome of the groundwater balance based on

- The recharge as derived from the flow records of a spring converted to monthly recharge values, which could then be expressed as a recharge coefficient in relation to the area recharge and the running average rainfall that best corresponds to the flow of the spring;
- The ratios of the chloride of the rainfall to measured chloride of the spring water, which should yield the same average recharge coefficient as that derived from the flow of the spring (see Eq. 3).

$$\frac{R_{av}}{Rf_{av}} = \frac{Cl_{Rf}}{Cl_{gw}} \quad \text{.......... Eq. 3}$$

Where R_{av} = the average recharge (mm) derived from the flow of the spring

Rf_{av} = the average rainfall for the corresponding period for which chloride has been measured.

Cl_{Rf} = the average chloride concentration of the rainfall, which is the unknown to be solved.

Cl_{gw} = the chloride of the spring water.

To derive the equivalent recharge (in millimetre of precipitation) from the flow of the spring, a probable recharge area could be used, which in relation to the average rainfall would provide the apparent recharge coefficients for each month. These coefficients should on average be the same as the ratio of the chloride concentration of the rainfall to that of the groundwater. Hence the rainfall chloride concentrations could be derived from the corresponding recharge values of months of which the chloride concentrations of the spring water have been measured. By an adjustment of the recharge area and the chloride concentration of the rainfall input, the most likely concentration of the rainfall and of the recharge area could thus be inferred.

Following this approach, reliable estimates of the recharge of several springs could be obtained as well as the sizes of the recharge areas, which could be compared to the probable boundaries that delineate the areas feeding the springs. If these areas turn out to be smaller than the areas bounded by dykes, the recharge occurring on the residual area would represent the losses from the system to adjacent compartments or water that is consumed, e.g. by wetlands.

Application of the method

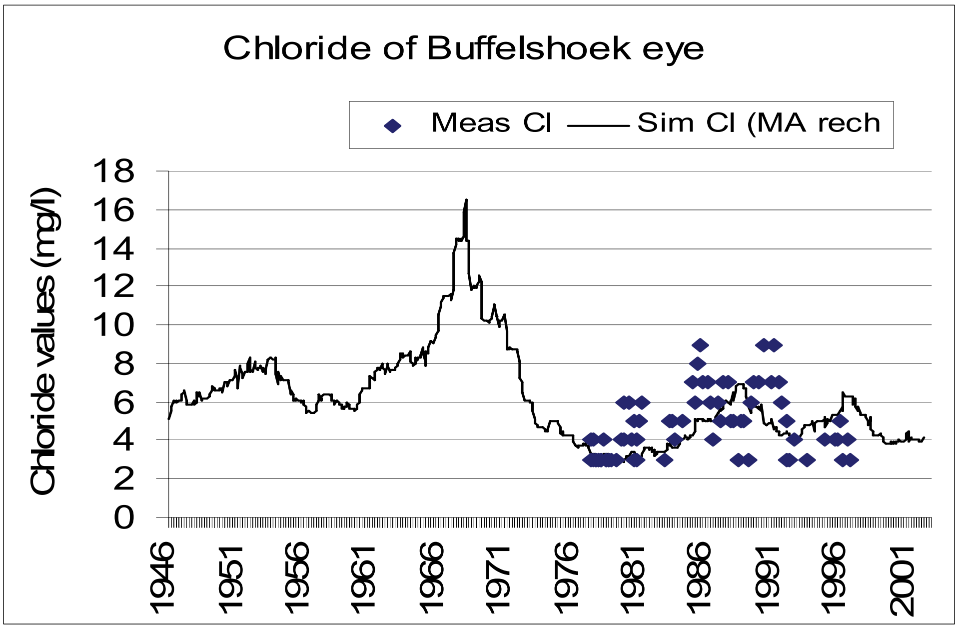


Figure 25. Simulated chloride concentrations of Buffelshoek spring in comparison to the measured values, which have yielded a reliable concentration of 0.56 mg/l for the rainwater based on a recharge area of 32 km^2 derived according to Figure 27.

Application of the indirect chloride method is illustrated for Buffelshoek eye, for which reliable flow data as well as the recharge area and a reasonable series of chloride measurements of the springs, are available. As has been indicated, the monthly flow of the spring could be simulated from the moving average rainfall over 36 months (see Figure 5) in relation to a recharge area of 32.6 km^2. The best match between the chloride concentrations that have been measured and those that have been simulated is indicated in Figure 25 for a value of 0.56 mg/l for the input chloride of the rainfall. This value is lower than that inferred from the regional relationship derived by Bredenkamp et al. (1995), that have been based on measurements of the chloride of rainfall samples available at the time (cf. Figure A1 in Appendix 1). The recharge area of 32.6 km^2 is closely the same as that delineated according to the bounding dykes (see Figure 26, which has been obtained from VSA). An area of 32.6 km^2 has been verified by the simulated drainage area derived from detailed piezometric contouring of a regional steady-state FEFLOW model (Van Rensburg, 2003) shown in Figure 27. Thus the inferred chloride of the rainfall that is derived from the match in Figure 25 is considered to be very reliable.

Similarly the best simulation (see Figure 28) of the chloride concentrations of Groot Kono eye in the Kuruman dolomite is obtained using the most probable recharge area according to the piezometric drainage area as delineated by Wiegmans (2004), i.e. an area ranging between 35 and 74.6 km^2 (see Figure 10). This converts to an average recharge coefficient of 0.049 of the average rainfall and an average input of the chloride of the rainfall of 0.36 mg/l. The average concentration of recently measured chloride in the rainfall is 0.32 mg/l.

For the Grootfontein Rietvlei spring close to Pretoria the outcome of the best simulation of the chloride values of the spring is shown in Figure 29.

The recharge of the Pretoria Grootfontein spring has been derived from the average rainfall over 36 months preceding a specific month that has been obtained from the recharge according to the ^{14}C simulations without incorporating the threshold rainfalls (see Figure 30).

For the Schoonspruit eye a reasonable long series of the chloride variations of the spring water has been obtained (see Figure 32) and the flow of the spring could be reliably simulated from the average rainfall over 72 months as is shown in Figure 31. This yielded a value of 0.63 mg/l for the best fit of the chloride of the rainfall in comparison to a value of 0.6 that has been measured by Veltman (2004).

The simulation of the chloride concentrations of Kuruman A spring is shown in Figure 33. The recharge has been derived from the MA method in relation to the average rainfall over 48 months with a recharge area of 258 km^2, which is slightly larger than the probable average recharge area of 229 km^2 according to VSA (preliminary piezometric contour maps). A chloride concentration of 0.47 mg/l for the rainfall showed the best overall match if the simulated series has been shifted forward by 100 months. This shift corresponds to the final lag of 97 months that had to be introduced to obtain the best ^{14}C simulation (see Figure F1 in Appendix 2).

The chloride concentrations of the rainfall that have been derived above compare reasonably well with the values, which have recently been measured at some of the springs as is indicated in Table 9 and Table 10.

It is recommended that further refinements of the chloride concentrations of the rainfall be made according to the annual precipitation, which in the case of Gaberone has indicated that the chloride in the measured rainfall samples declines as the rainfall increases (see Figure 24). It is of critical importance to determine the chloride concentrations of the rainfall and of the spring water reliably to obtain independent estimates of the recharge and of the areas feeding the springs. This area has to be compared to the probable recharge area and if there is surplus recharge available it could be provided for other users. It is important to proceed with further measurements and estimations of the rainfall chloride according to the indirect method, in order to derive the regional variability of the chloride input from rainfall for all regions of South Africa, as the chloride mass balance (CMB) is the main basis for the determination of the potential and of the reserves of most aquifers.

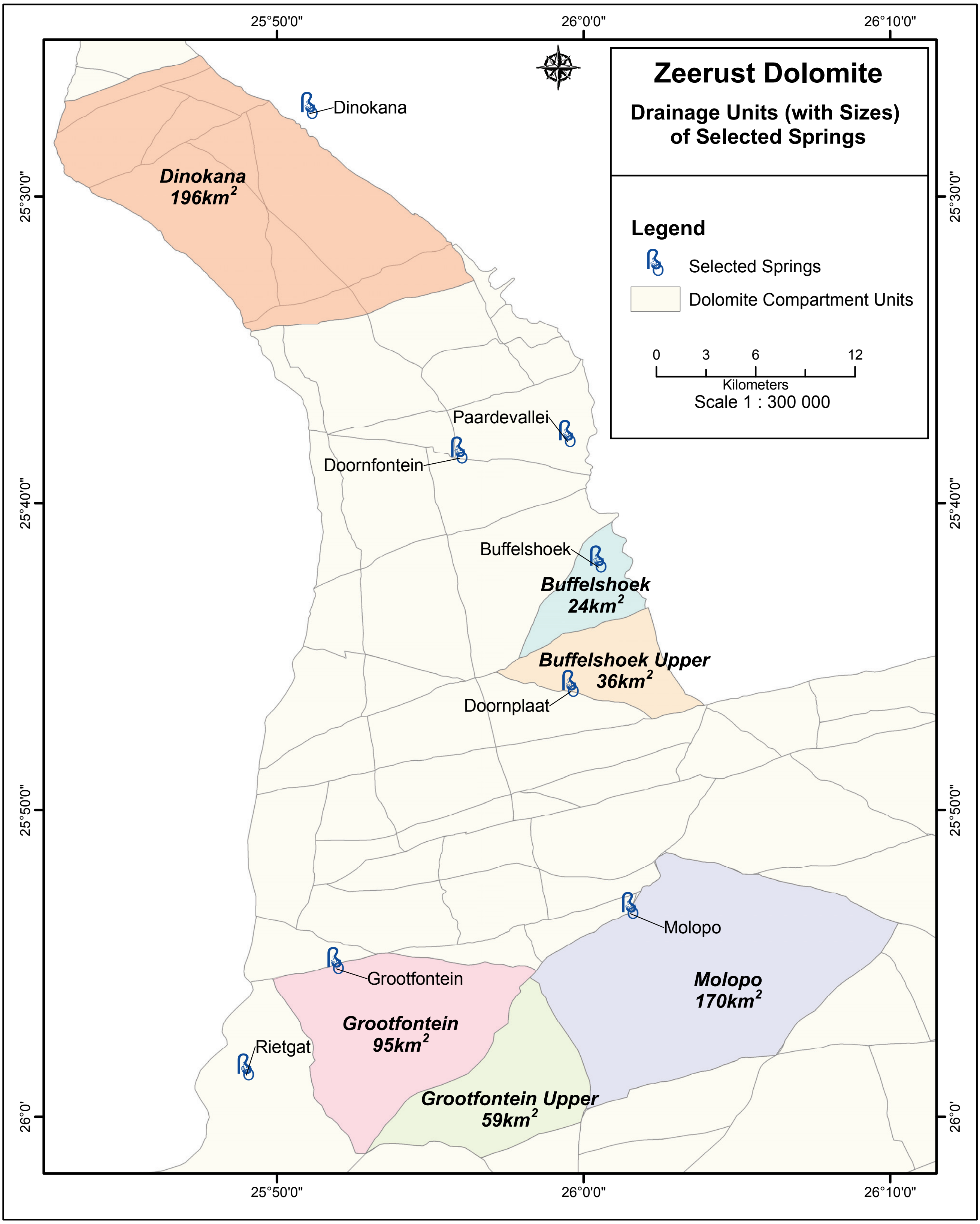


Figure 26. Some prominent dolomitic compartments in the Northwest region and springs they recharge. As is indicated in Figure 27 the real area contributing to the spring flow is more complex.

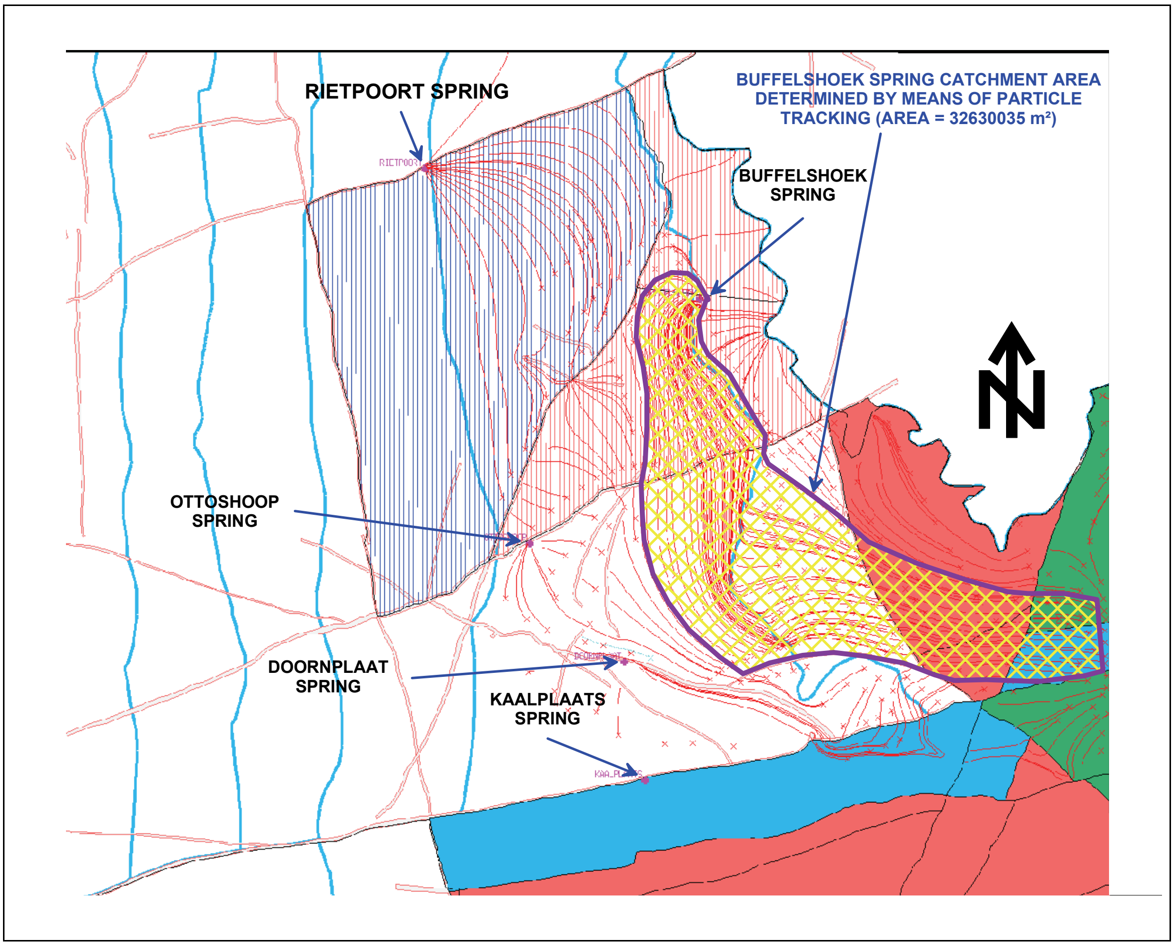


Figure 27. Drainage area that feeds the Buffelshoek spring, derived from particle tracking of a steady-state FEFLOW model of a large dolomitic area indicating a recharge area of 32.6 km^2 (figure by Van Rensburg, 2005).

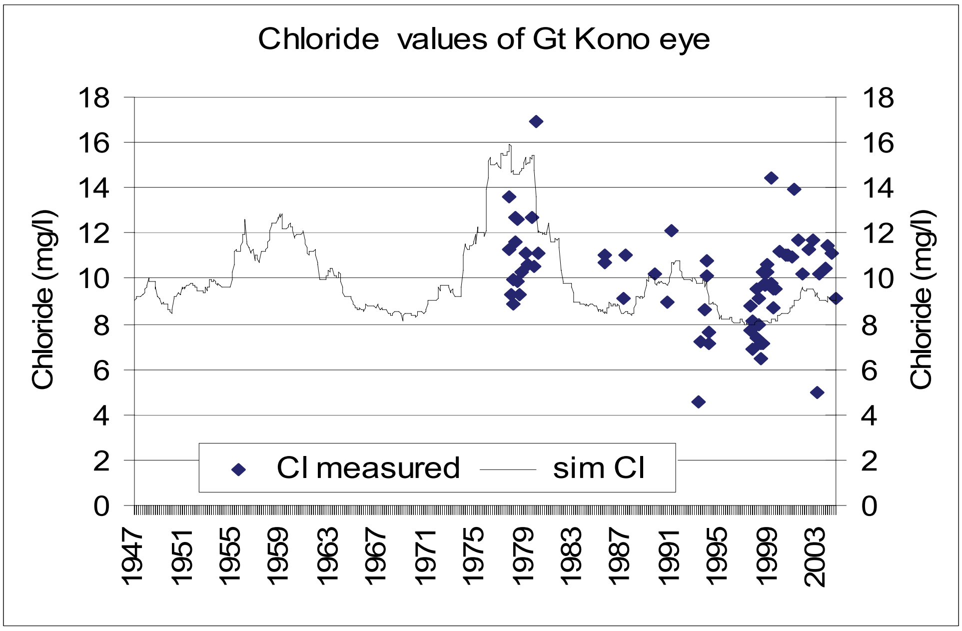


Figure 28. Graph of the measured and simulated chloride values of Groot Kono eye. The monthly recharge has been derived for an area of 34 km^2 with an average chloride concentration of 0.40 for the rainfall. This area size falls within the preliminary delineation of the recharge area.

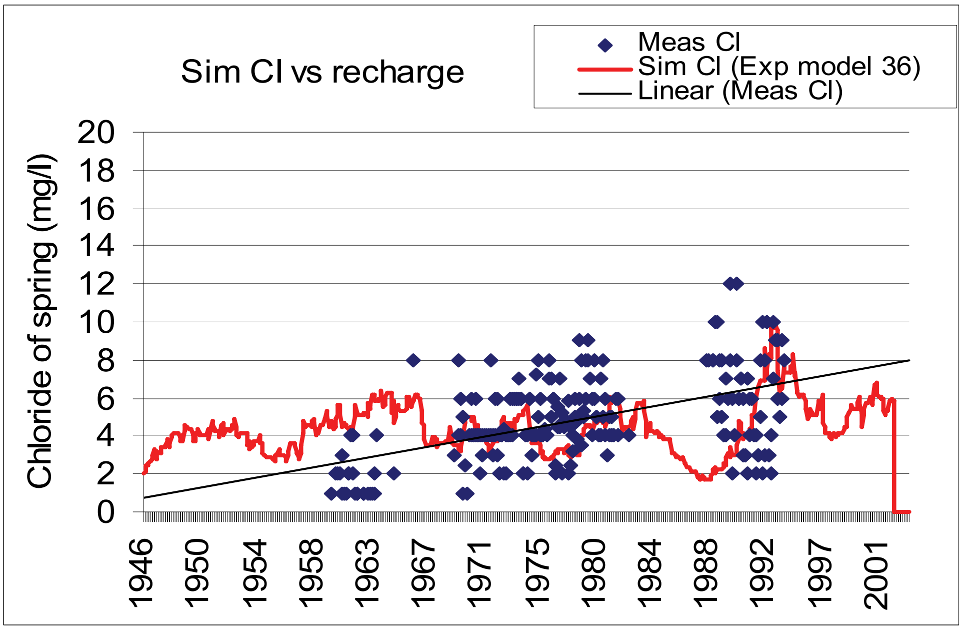


Figure 29. The measured chloride concentrations of the Pretoria-Grootfontein eye in comparison to those simulated if the chloride concentration of the rainwater is 0.65 mg/l. The increasing trend is an indication that the spring has gradually been polluted (also see Figure 9).

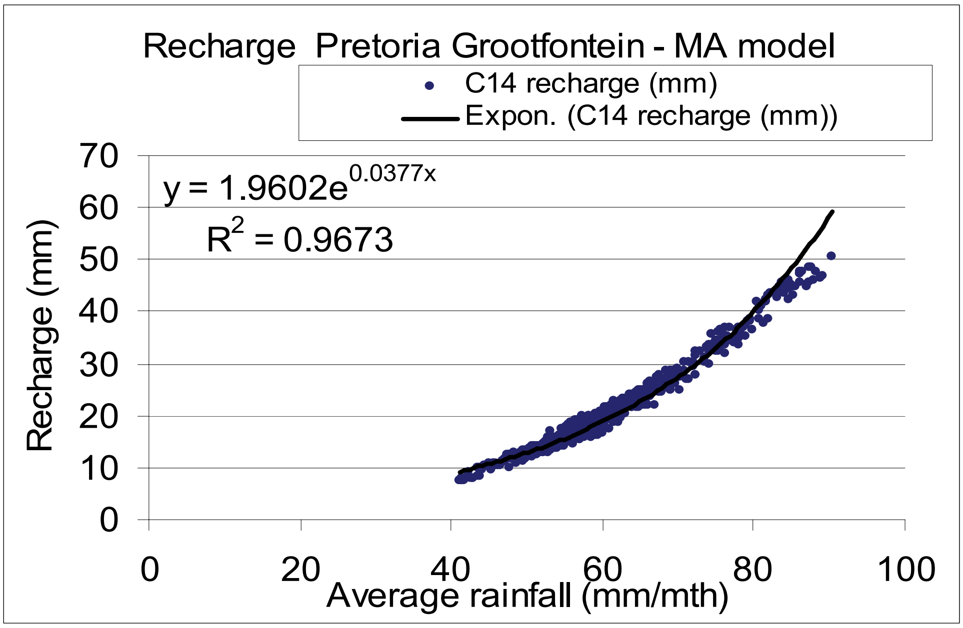


Figure 30. Exponential relationship between the monthly recharge derived from the ^{14}C simulation model and the average rainfall over the preceding 36 months without the incorporation of the threshold rainfalls.

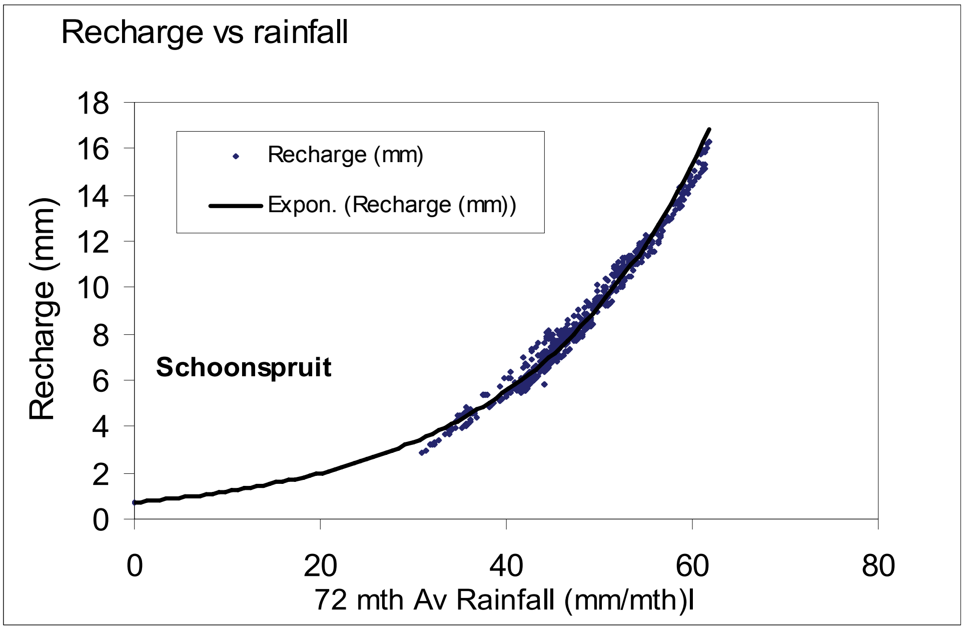


Figure 31. The monthly natural flows of Schoonspruit eye (mm/month) in relation to the average rainfall over 72 months for a recharge area of 842 km^2 as derived by Veltman (2003).

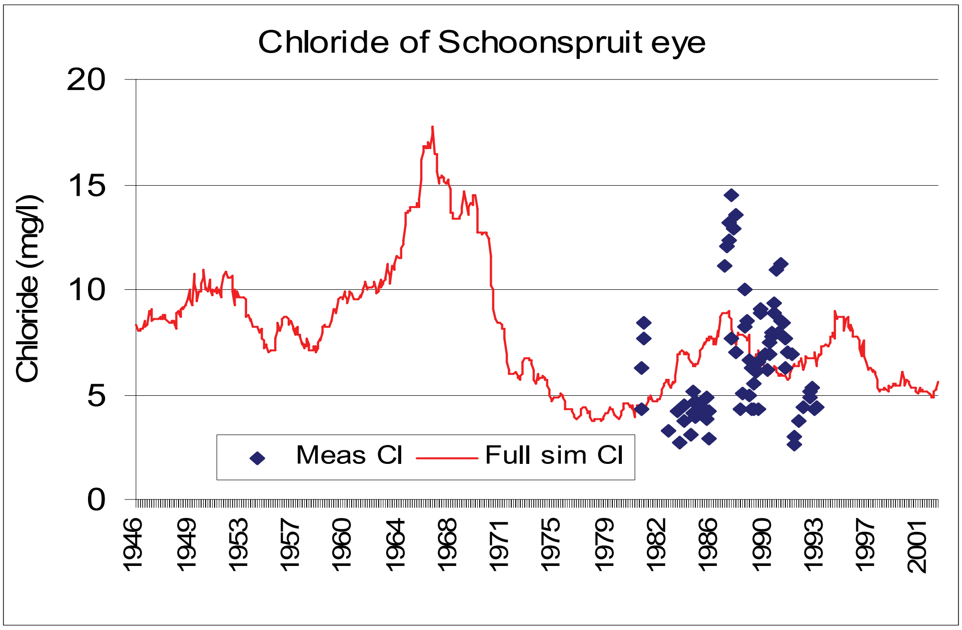


Figure 32. Simulated chloride values for Schoonspruit derived from the recharge coefficients of the monthly recharge that has been obtained from the relationship shown in Figure 31 for a recharge area of 842 km^2 (Veltman, 2003). This yielded a value of 0.63 mg/l for the best fit of the chloride of the rainfall in comparison to a value of 0.6 that have been measured by Veltman (2004).

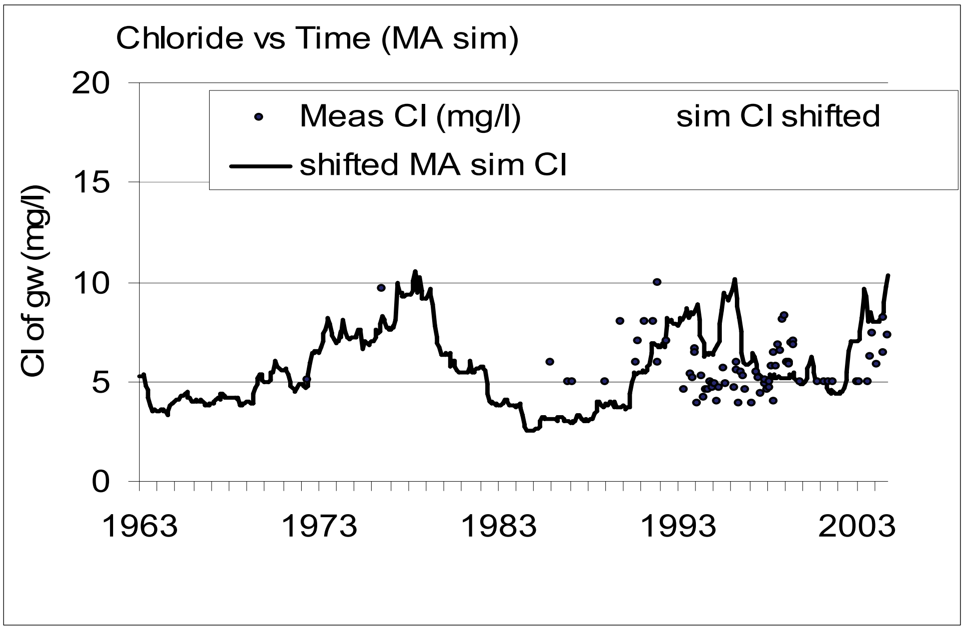


Figure 33. Comparison of the simulated and measured values of the chloride concentrations of the Kuruman A spring, based on recharge from an area of 258 km^2 and a concentration of 0.47 mg/l for the chloride of the rainwater.

Table 10. A comparison of the simulated and measured chloride concentrations of the rainfall in different areas.

Spring/Area	**Simulated Cl of rain (mg/l)**	**Measured Cl of rain (mg/l)**	**Comments**
Buffelshoek eye	0.56	Not measured	Area and recharge is reliable.
Schoonspruit eye	0.63	0.6	The measured value by Veltman (2003).
Pta Lynwood (rainfall sampling)		0.35 to 0. 55 (0.47) weighted 0.32	Rainfall sampled by Water Affairs (Pretoria Lynwood). This implies that the recharge is much lower and the recharge area of the spring is larger than has originally been assumed.
Pta Grootfontein	0.65	0.32 to 1.1 (0.47) weighted value	The measured chloride for the period 2002 to 2004 shows a large variation but if it is representative of the long-term average the recharge must be smaller and the recharge area correspondingly larger.
Groot Kono eye (Kuruman)	0.35	0.40 to 1.1 (rain Bokfontein)	Measured values only for 2005. Recharge area to be checked against the probable maximum area.
Kuruman eye	0.47	0.32	Rainfall samples over the period April 2004 to May 2005.

Section 9. Estimating the average turnover time and age of the water in dolomitic aquifers from the ^{14}C modelling.

The average turnover time of water in a dolomitic aquifer can be calculated from the average age of the mixture of the shallow flow with the deep flow component, according to their relative contributions to the flow of a spring (^{14}C method). The turnover time, expressed in years, represents the groundwater in storage as multiples of the average annual recharge.

To calculate the average age of the water in the aquifer, the final lag time by which the entire simulated ^{14}C pulse was shifted has to be added to the turnover time, but it is not included in determining the storage water.

9.1 Incorporation and explanation of lag times in the ^{14}C model

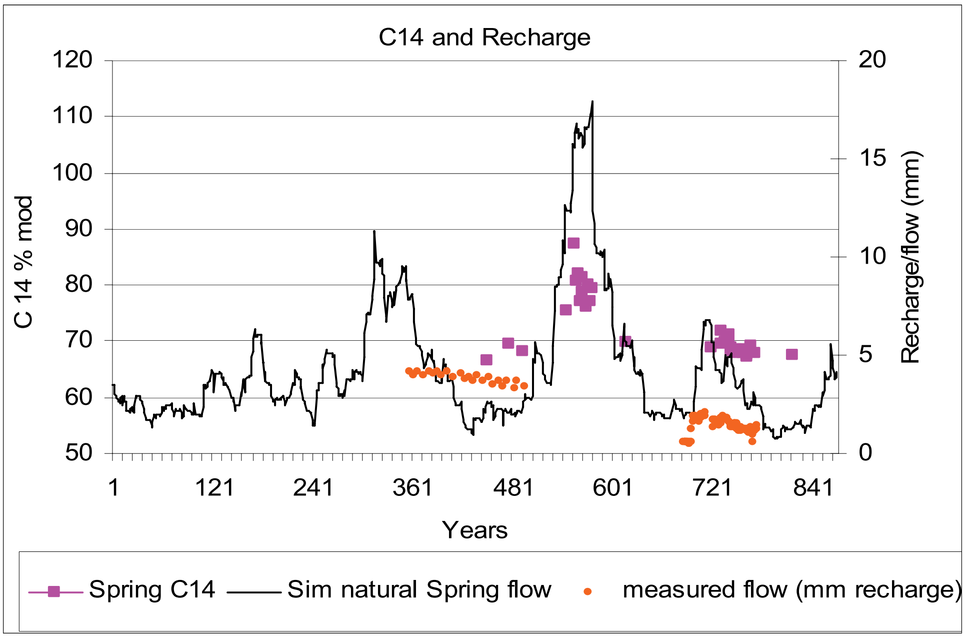


Figure 34. The best correspondence between the simulated natural flow of Kuruman A spring and the measured ^{14}C.

The following lag times had to be incorporated in the ^{14}C model:

- The lag caused by averaging the monthly recharge over a preceding period (e.g. the values appearing in the tables for period 1 and 2).
- The final lag times to shift the entire simulated series so that it better fits the observed data.

The latter incorporate:

- The lag resulting from water that is temporarily contained in the unsaturated overburden covering the aquifer and which is still percolating to the saturated zone, then only becoming part of the saturated flow regime.
- The lag due to exchange with water contained in the aquifer matrix, which although less mobile than the water moving through the karstified zones, is also part of the total water stored in the aquifer. The latter accords with the findings of Shapiro (2001) based on tracer

experiments, which indicated that the matrix water is an active part of dynamical flow in an aquifer. A long lag is typical of the larger compartments, but in the case of Rietgat (with a small recharge area) a lag of 81 months has produced the best simulation (see Figure B1). The final lag is attributed to the slow piston-like displacement of recharge percolating through the calcrete matrix. (If it had not been for this lag the peak of the ^{14}C input pulse would have been missed).

The final lag times actually are the number of months by which the rainfall sequence has to be shifted back in time to yield the observed ^{14}C response of a specific month. This means that the observed ^{14}C concentrations of a particular month represent the outcome of recharge from rainfall of a preceding period equal to that of the final lag. This corresponds to the finding of Bredenkamp (2000) that the measured ^{14}C concentrations of the springs corresponded best to the flow of a spring averaged over a period, which is closely the same as the final lag time used in the ^{14}C model (see Figure 34).

9.2 Turn-over time (mean residence time) and age of water in the aquifer

The average turnover times of the different spring-flow systems as inferred from the ^{14}C model, are listed in Table 11 and have been calculated according to the following formulas (Vogel and Bredenkamp, 2005):

Turnover time (yrs): $T = \dfrac{(0.5n_1 + 0.5(n_2 + 1 + n_2)m}{12(m+1)}$

Where n_1 = the length of period 1 in months

n_2 = the length of period 2 in months

m = the multiples of deep flow relative to the shallow flow component

Age of the water (yrs) = Turnover time (yrs) + Final lag (months)/12

The turnover time could also be ascertained from the simulated tracer responses over time. Intuitively it is expected that it will take a long time for an injected tracer to be flushed out of the system. The following could be inferred from a visual inspection of the simulated ^{14}C contents for three typical springs:

- Rietgat (see Figure 7): If one disregards the initial lag period it is evident that the output response is the same as that of the input ^{14}C. This is because there is no component of deep flow in this system that could dilute the inflow significantly. The only change in the input is effected by the dissolution of the bicarbonate according to the dual-recharge process, which is determined by the rainfall. Natural levels of ^{14}C in the groundwater will apparently be reached after a period of about 50 years since the tracer injection.
- Olievendraai (see Figure B2): This spring is situated on the northern bank of the Molopo River and issues from a small compartment that already shows signs of pollution, which confirms the admixture of recent water as has been indicated by the high ^{14}C content. According to Figure B2, the average duration of the impact of the thermonuclear ^{14}C input pulse to pass through the aquifer would be significantly longer than 15 years, because of the dilution and dispersion of the influx ^{14}C pulse by the deep flow component. The latter, according to the model, is equivalent to the influx component. Thus the period for the total ^{14}C pulse to exit from the aquifer is about 100 years.

- Buffelshoek (see Figure B1): According to the simulation model, 3.19 times the shallow component is contributed by the deep flow component (see Table 3). This causes a long drawn-out response of the ^{14}C after the peak has been reached (see Figure B1). The recession of the ^{14}C pulse in this case would exceed 200 years, which highlights the prolonged effect pollution would have in some of the dolomite compartments.

Table 11. Comparison of the turnover times of water in the different dolomitic compartments

Grootfontein Zeerust springs	Turnover (years)	Marico Schoonspruit	Turnover (years)	Pretoria Springs	Turnover (years)	West Rand springs	Turnover (years)	Kuruman springs	Turnover (years)
Buffelshoek	11.6	Marico	8.8	Erasmus	20.3	Gerrit Minne	22.0	Kuruman A	22.40
Olievendraai	8.6	Schoonspruit	12.2	Grootfontein	12.7	Turffontein	17.3	Kuruman B	27.33
Gftn Molopo	12.8	Upper Mooi	13.4	Pretoria Upper	18.3			Manyeding B	7.43
Molopo	21.9	Maloneys	16.1	Pretoria Lower	16.8			Groot Kono	8.57
Rietgat	1.5	Renosterfnt	15.9	Sterkfontein	18.8			Klein Kono	10.86
Vergenoeg	10.6								
Doornplaat	12.5								
Doornfontein	9.1								
Paardevlei	10.0								
Lichtenburg	10.8								
Dinokana	12.5								
Stinkhoutb	10.1								

Section 10. Estimating the depth of a dolomitic aquifer

It is difficult to derive the depth of an aquifer and it is usually obtained by examining the drilling logs of boreholes and the deepest water strikes. However, Bredenkamp (2000) has indicated that the effective depth of an aquifer can be inferred from the accumulated rainfall over a period that best mimic the temporal fluctuations of the monitored series of groundwater levels (a variation of the MA method). Relating these depths to the storativity values that have been inferred from the MA simulations of the groundwater levels indicated that the aquifer specific yield decreases according to a power function (Figure 35) but also corresponds reasonably to an exponential relationship. The exponential equation yields a S_y value of 0.04 at the water table (S_{y0} for depth = 0), which represents the effective specific yield assuming the aquifer to have uniform specific yield (Bredenkamp and Vogel, 1970).

In the case of an isotropic aquifer of which S_y declines exponentially with depth, Eq. 4 has been derived (Vogel, 1967):

$$T = \frac{Sy_0 D}{R} \quad \text{Eq. 4}$$

Where

T is the turnover time of the spring water; R is the average annual recharge and

D is the effective aquifer thickness with a uniform specific yield of Sy_0, which represents the porosity at the top of the saturated aquifer.

For the Grootfontein aquifer a value of S_{y0} = 0.015 to 0.03 has been derived by Van Rensburg (1995) and 0.0395 by Bredenkamp (2005).

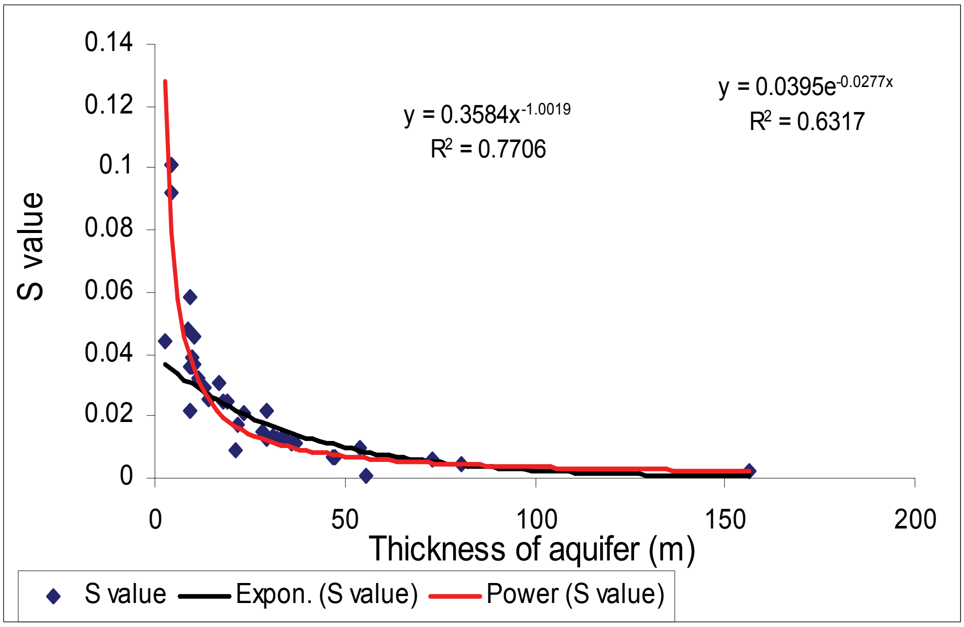


Figure 35. Specific yield (S_y)versus depth of the NW dolomitic aquifer indicating a power function or an exponential decline in aquifer storage.

In the case of Grootfontein (Molopo area) the effective depth D of the aquifer, assuming that the storativity S_{y0} = 0.04 and is not declining with depth, could be derived from Eq. 4, by inserting the average recharge of 49 mm/month that has been derived from the ^{14}C simulation and a turn-over time of 12.8 years (see Table 3 and Table 11).

$$D = 12.8 * 49.8 /1000/0.04$$

$$= 15.9 \text{ m}$$

This depth is about 65 % the effective depth of 25 m that has been derived according to the exponential decline in specific yield shown in Figure 35. The total effective depth of the aquifer with declining porosity appears to be in the range of 150 metres with an insignificant contribution of water from greater depths.

According to the turnover time, the storage of water in the Grootfontein aquifer is 12.9 times that of the average annual recharge. However, according to the lag-shift and findings of Shapiro (2001), a portion of this water is contained in the aquifer matrix and in the unsaturated zone, and not all of it is available for abstraction. Similarly, abstraction from depths in excess of 100 m would also be uneconomical to utilize.

The fact that dolomitic aquifers could represent a highly anisotropic storativity and permeability conditions, e.g. with double or triple porosity, could question the applicability and reliability of eq. 4. However, the fact that fairly consistent results have been obtained for dolomitic aquifers in different dolomitic formations, conforms with the outcome of tracer tests by Shapiro (2001), which have indicated that despite the occurrence of zones of high permeability, the flow and mixing of the groundwater is determined by the average characteristic of the aquifer.

Section 11. Deriving a simple recharge-rainfall relationship from the ^{14}C simulations

It is a common-practice to derive the recharge according to a simple recharge-rainfall relationship that could be generally applied in dolomitic aquifers. The most simple equation is a linear recharge relationship of the type:

$$R_{av} = b.Rf_{av} \qquad \text{Eq. 5}$$

where R_{av} = the average recharge

Rf_{av} = average rainfall

b = the recharge coefficient

Assuming that recharge only occurs if the rainfall of a particular month exceeds a certain threshold, and the recharge coefficient b is weighted proportional to the average rainfall over a period being higher or lower than the long-term average rainfall of the series, recharge would yield a non-linear relationship with rainfall (see Eq. 1).

Similarly it has been attempted to derive a simple recharge-rainfall relationship for the bimodal recharge that have been successfully used in the ^{14}C simulations. The following quadratic equation can reliably simulate the average recharge of a specific month contributed from the bi-modal recharge components:

$$R_i = p\frac{1}{n}\sum_{i=1}^{i=n} Rf_i^{\,2} + q\frac{1}{n}\sum_{i=1}^{i=n} Rf_i + r \qquad \text{Eq. 6}$$

where p, q = the regression coefficients and

r = constant

n = the number of months in the rainfall series

A typical example for Kuruman A spring is shown in Figure 36 indicating the best fit (correlation coefficient $R^2 = 0.89$) that has been obtained for the quadratic recharge equation. Another good match has been obtained for an exponential equation ($R^2 = 0.84$), that is similar to the one derived by Van Rensburg (1995):

$$R_i = b\frac{1}{n}\sum Rf_i.e^{ax} \qquad \text{Eq. 7}$$

Where b = recharge coefficient;

a = exponential factor and

$\sum Rf_i$ = the average rainfall over the previous n months.

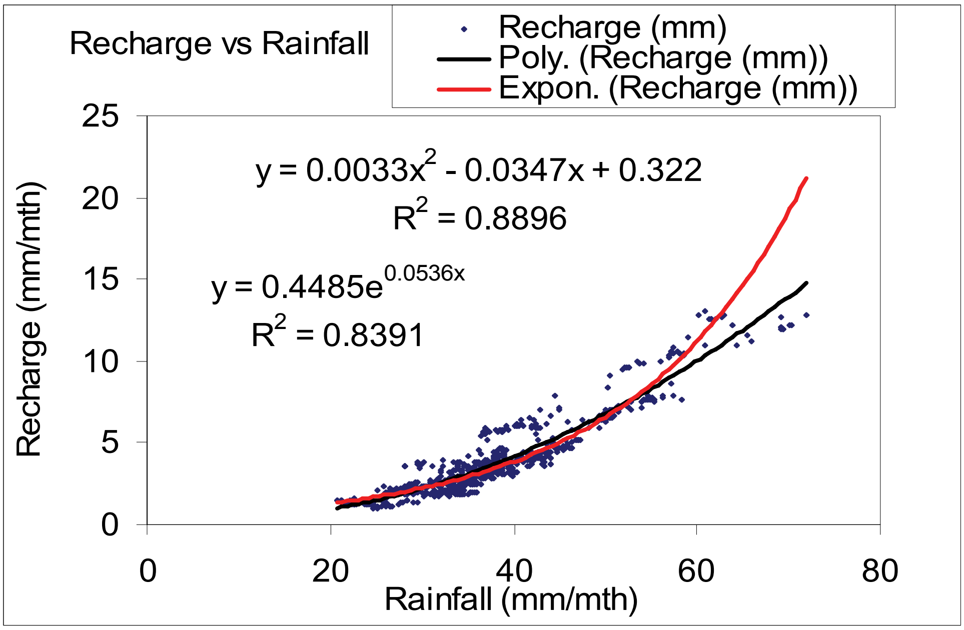


Figure 36. The monthly recharge derived from the simulation of the flow of the Kuruman A spring by incorporating threshold rainfalls. These were correlated to the average rainfall over the preceding 48 months disregarding the threshold rainfall values.

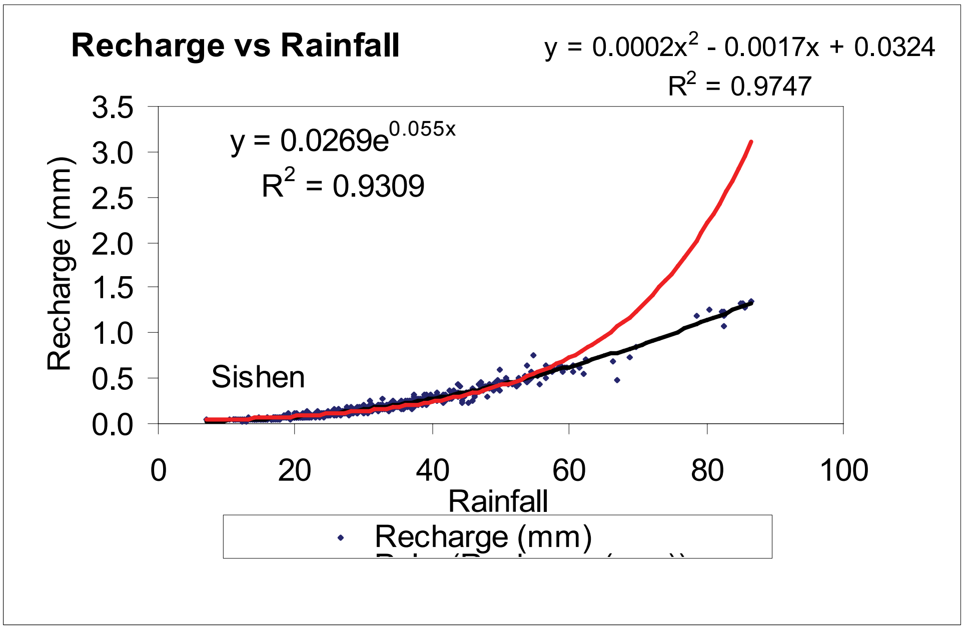


Figure 37. Best relationship for Sishen between the average rainfall over the preceding 12 months and the monthly recharge derived from the effective rainfall without incorporating the threshold rainfall.

For the Sishen aquifer the rainfall-recharge relationship shown in Figure 37 has been obtained.

Although the recharge of individual months depends on the rainfall exceeding the threshold rainfall and the weighting factor that has been derived from the ^{14}C simulations, it reduces to a simple equation in relation to the average rainfall over the preceding 12 months without any threshold rainfalls. For each of the springs a similar recharge-rainfall equation has been obtained and the respective equations are shown in the corresponding figures in Appendix 6.

Section 12. Validation of the ^{14}C model

12.1 The Excel model

An Excel model has been compiled by the Groundwater Group of the University of the Western Cape (UWC), attempting to simulate the breakthrough response of the ^{14}C input according to different tracer models. A model of the time-variant output through a section of the aquifer has been constructed. However, even the best model showed a rather poor simulation (see Figure 38) and could not adequately reproduce the rapid ^{14}C increase of the spring outflow caused by the injected pulse. The modelling package is described in Appendix 7 and is available as a visual-basic package from UWC, capable of simulating exponential flow, piston flow and dispersion flow conditions. It could be used as a demonstration tool for comparison of different mixing and tracer interactions but proved to be inferior to the present empirical mixing model.

The simulation indicates that the discharge of the spring does not correspond to a single exponential mixing model of the input recharge and it would have to be modified to incorporate a two-box model and the lags indicated by the empirical model of the present study.

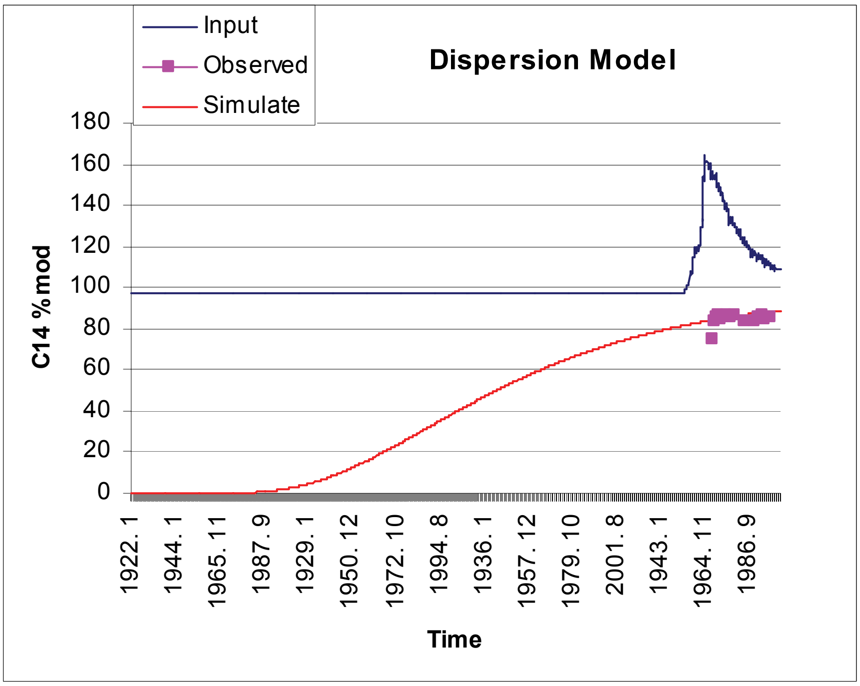


Figure 38. The measured versus the ^{14}C values that have been simulated by an Excel analytical model (Groundwater Group of UWC).

12.2 Simulation of the Grootfontein aquifer (Molopo) by FEFLOW

Grootfontein-Molopo aquifer

In view of the unconvincing simulation that has been obtained from the simplified Excel model, a FEFLOW mass-transport simulation of the ^{14}C appearance in the Grootfontein-Molopo aquifer has been attempted for a vertical section through the aquifer (Van Rensburg, 2005). This has not been part of the original objectives of the present project.

The section of the aquifer comprised a grid of finite elements over an aquifer length of 15 km and a depth of 150 m. The following sets of different specific yield (S_y) and hydraulic conductivity values (K) have been assigned to the finite elements, and the recharge according to the best simulation for the Grootfontein aquifer model used in this project.

- Scenario A: Both K and S_y values decline exponentially with depth, starting with an S value of 0.04 at the top of the aquifer and declining for each of the 12 zones down to a depth of 150 m.
- Scenario B: The same as for Scenario A but with the initial S_y value starting at 8 % which is more in line with the S values shown in Figure 35.
- Scenario C: The same as scenario B with the initial S value starting at 8 % but inserting another layer of high permeability with the same exponential decline of K and S_y deeper down the aquifer. This is the closest resemble of two-reservoir mixing model with the deeper zone of high permeability contributing some of the delayed recharge to the spring with a different lag.

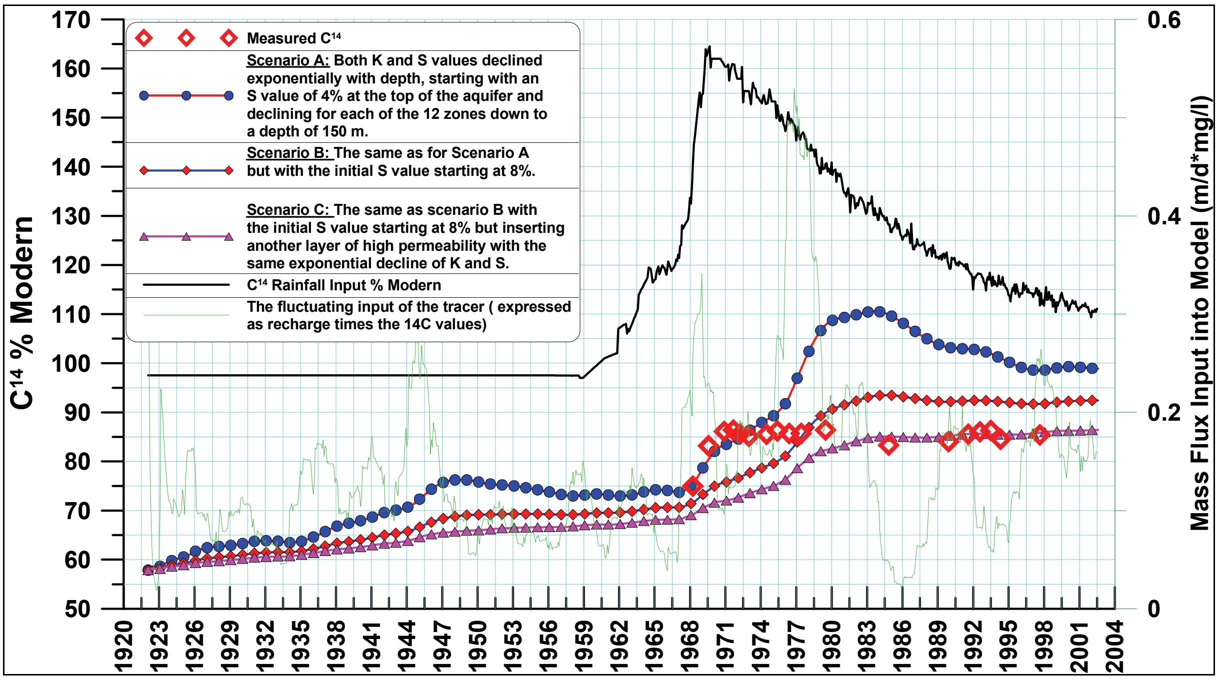


Figure 39. The results of the simulations of ^{14}C of the Grootfontein aquifer (Molopo area) based on a FEFLOW hydrodynamic model (Van Rensburg, 2006) in comparison to the measured ^{14}C values. The fluctuating input of the tracer (expressed as recharge times the ^{14}C values) is shown by the green graph.

The variable input of tracer to the aquifer (^{14}C times recharge) occurred according to the bi-modal recharge principle and is presented by the graph in green. The influence of the unsaturated zone has not been incorporated in the model but its effect has also been observed according to the final lag that had to be applied to obtain the best simulation.

Figure 39 shows the simulations for ^{14}C input according to the simulated recharge for Grootfontein aquifer.

In view of the time required for equilibrium to establish a steady-state pre-run of the model with essentially a constant ^{14}C input from the rainfall, it was required to obtain the starting ^{14}C concentrations in 1922. This indicated a value of about 58 % modern ^{14}C and the best simulations have been obtained for scenarios B and C where both S and K values decline exponentially with depth. At this stage no further refinement of the model has been carried out pending testing of a 3-dimensional model. The latter is required to first assess the impact lateral spatial inflow would have on the simulated tracer output.

Rietgat aquifer

The second FEFLOW simulation has been performed for the Rietgat aquifer being recharged from a small area showing a more rapid through-flow of the ^{14}C pulse at the spring, although appearing with a substantial lag. This is evident from the shape of the output ^{14}C response with no deep flow component (see Figure 7). The variable input of the ^{14}C load (^{14}C times recharge) is shown by the green-shaded graph in Figure 39. The output of the hydrodynamic mixing/dispersion of the ^{14}C has been simulated according to different scenarios of declining hydraulic conductivity (K) and storativity (S_y) of the aquifer with depth (see Table 12).

Table 12. Different scenarios of K and Storativity (S_y) used in a FEFLOW simulation of environmental ^{14}C transport through a section of a dolomitic aquifer to the spring outlet.

Layer	*To depth*	*Scenario 1*	*Scenario 1*	*Scenario 2*	*Scenario 2*	*Scenario 3*	*Scenario 3*	*Scenario 4*	*Scenario 4*	*Scenario 5*	*Scenario 5*
	Meter	K-value m/s	Storativity Sy	K-value m/s	Storativity Sy	K-value m/s	Storativity Sy	K-value m/s	Storativity Sy	K-value m/s	Storativity Sy
1	-12.5	6.20E-05	8.0E-02	6.20E-05	4.00E-02	3.10E-05	4.00E-02	6.20E-05	8.00E-02	2.31E-04	8.00E-02
2	-25.0	5.70E-05	7.32E-02	5.70E-05	3.66E-02	2.85E-05	3.66E-02	5.70E-05	4.00E-02	1.16E-04	7.32E-02
3	-37.5	5.20E-05	6.64E-02	5.20E-05	3.32E-02	2.60E-05	3.32E-02	5.20E-05	2.00E-02	5.79E-05	6.64E-02
4	-50.0	4.70E-05	5.95E-02	4.70E-05	2.98E-02	2.35E-05	2.98E-02	4.70E-05	1.00E-02	2.89E-05	5.95E-02
5	-62.5	4.20E-05	5.27E-02	4.20E-05	2.64E-02	2.10E-05	2.64E-02	4.20E-05	5.00E-03	1.45E-05	5.27E-02
6	-75.0	3.70E-05	4.59E-02	3.70E-05	2.30E-02	1.85E-05	2.30E-02	3.70E-05	2.50E-03	7.23E-06	4.59E-02
7	-87.5	3.20E-05	3.91E-02	3.20E-05	1.96E-02	1.60E-05	1.96E-02	3.20E-05	1.25E-03	3.62E-06	3.91E-02
8	-100.0	2.70E-05	3.23E-02	2.70E-05	1.62E-02	1.35E-05	1.62E-02	2.70E-05	6.25E-04	1.81E-06	3.23E-02
9	-112.5	2.20E-05	2.55E-02	2.20E-05	1.28E-02	1.10E-05	1.28E-02	2.20E-05	3.13E-04	9.04E-07	2.55E-02
10	-125.0	1.60E-05	1.86E-02	1.60E-05	9.30E-03	8.00E-06	9.30E-03	1.60E-05	1.56E-04	4.52E-07	1.86E-02
11	-137.5	1.10E-05	1.18E-02	1.10E-05	5.90E-03	5.50E-06	5.90E-03	1.10E-05	7.81E-05	2.26E-07	1.18E-02
12	-150.0	6.00E-06	5.00E-03	6.00E-06	2.50E-03	3.00E-06	2.50E-03	6.00E-06	3.91E-05	1.13E-07	5.00E-03

For the Rietgat simulation the FEFLOW model was constructed for a section of 4 km in length and a depth of 150 m, whereas for Grootfontein the length was 15 km and the depth the same. The best simulation has been obtained for scenario 5 with K values declining exponentially with depth, and storativity declining linearly for the different layers down to an assumed final depth of 150 meters (see Figure 40 and Table 12). For this model a final lag of 56 months had to be applied, i.e. 30 months less than the 86 months, which had been obtained for the simulation of Rietgat - see Figure 7a and Table 2. Another good fit to the observed measurements is that of scenario 2 where both K and S_y decline linearly with depth (see Figure 41). However, for the latter simulation the amplitude of the pulse is higher than for scenario 5.

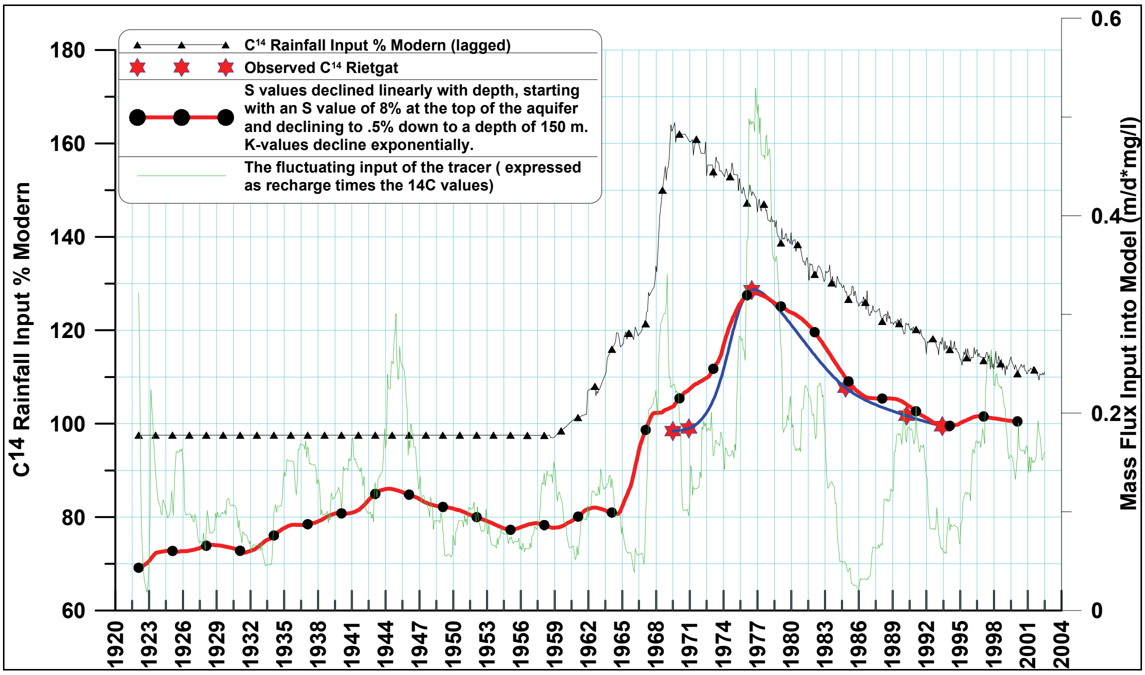


Figure 40. Best simulation of the FEFLOW hydrodynamic flow model for K and S_y reducing by 50 % for each deeper-lying layer of the aquifer (Scenario 5).

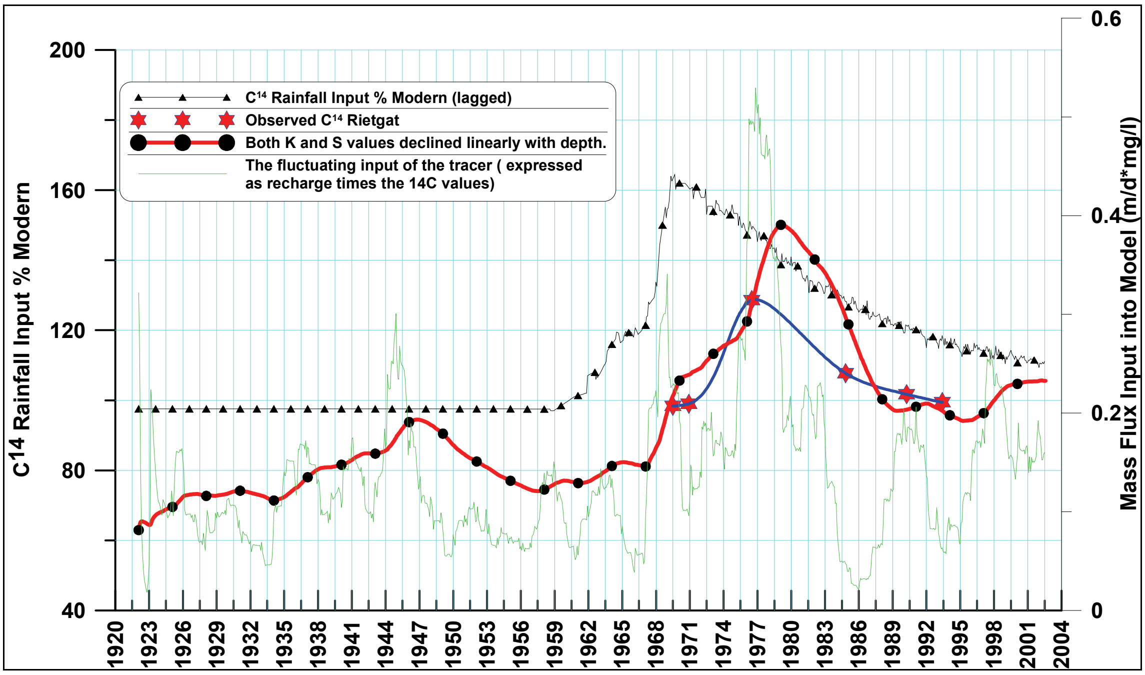


Figure 41. Outcome of the FEFLOW simulation model according to Scenario 2 with both K and S_y declining linearly with depth.

Figure 40 represents the best of the simulations that has been obtained for scenario 5, with S_y declining linearly with depth and K values decline exponentially (see Table 12).

In view of the long lead-time that is required for an aquifer to establish equilibrium, the ^{14}C concentration of the spring started at a higher value than zero (63 % modern), to obtain the best simulations. This value is lower than the equilibrium values that have been obtained in the empirical model and requires further scrutiny. Better simulations have been obtained with FEFLOW than with the EXCEL model and the results have been as good as those simulated from the conceptual ^{14}C model of Vogel and Bredenkamp (2005), and Bredenkamp and Van Wyk (2005).

The successful simulation of the ^{14}C values of the Rietgat spring by means of the FEFLOW model marks a significant advance towards reliable simulation of the flow and transport of environmental tracers in spring-flow systems. It appears that the differential input of ^{14}C according to the conceptual model and the declining storativity and K values could be the key to the improved simulation. It was also clearly indicated that the response of the ^{14}C is dependent on the dimensions of the model and apparently controls the size of the box representing the young water in the empirical model.

It is most important to extend the XZ-section simulations to a full 3-dimensional FEFLOW model of the aquifer to incorporate the admixture of the spatial contribution of ^{14}C to the spring according to the dimension/shape of the aquifer.

Section 13. Discussion of the success of the project in relation to the objectives and application prospects

Successful modelling of the ^{14}C concentrations of the recharge input and its mixing with water transported in the saturated dolomitic aquifer under natural flow conditions, has been achieved with the conceptual simulation model. Although the model could be criticized in terms of the number of variables to obtain a good fit, these parameters comply with the hydrogeological concepts that control the mechanism and distribution of recharge from rainfall and according to differences of the catchment areas; also the mixing that occurs in the unsaturated zone overlying the real aquifer, and of the transient flow through the saturated aquifer. A bi-modal input of the ^{14}C that is controlled by a low and high rainfall threshold, has effected good simulations of the ^{14}C content. It probably explains why good simulations has been obtained for the FEFLOW model for declining porosity and permeability, which accounts for a larger component of younger water to the spring flow for the same hydraulic head. It also explains why water with concentrations of ^{14}C in the range of 55 % to 65 % modern could still be attributed to recent recharge.

The ^{14}C recharge model could also explain the differences in the responses of tritium and CFC as being attributable to their flow paths and input into the saturated zone of the aquifer. It furthermore complied with the hydrological evidence indicating that the groundwater is essentially young water. This has enabled the following to be derived from the study:

The recharge in relation to the rainfall indicated that it comprises a normal and a direct component, which determines the bicarbonate and ^{14}C concentrations of the spring waters.

- The mixing of the dual-recharge components occurred according to a two-box model with more recent recharge contained in the first box. The concentration of ^{14}C in this box is admixed with a larger component of deep water, which is a mix of water being recharged further back in time and at greater distances from the spring. To obtain the best ^{14}C simulation the relative contributions from the two boxes were adjusted. At all times the relative contributions of the deep and shallow components are controlled by the hydraulic head, which is determined by the recent recharge.

- The turnover times of water in the different aquifers, which have been obtained from the ^{14}C modelling, has been used to estimate the groundwater in storage as multiples of the average annual recharge. This is regarded as a significant contribution to the assessment and utilization of groundwater resources in periods of extreme drought. However, as this component also incorporates water that is contained in the aquifer matrix, it could induce a false reliance on the storage water, as the abstraction of such water is controlled by the availability of large fractures or dissolution channels where sufficient water could accumulate to be abstracted at high yields. The apparent high storage of water in the aquifer could also lead to overexploitation relative to the reserve status of the aquifer that has to be maintained. The determination of the reserve by the Department of Water Affairs needs revision according to the outcome of the ^{14}C modelling and the simulation of the flow of the springs.
- It has been found that the recharge derived from the ^{14}C model could vary while good simulations of the ^{14}C can still be achieved. This is contrary to earlier claims that the ^{14}C simulations provide an independent method of determining the recharge and its controls. The high and low rainfall thresholds still apply to obtain the relative contributions from the bi-modal recharge, but the recharge coefficients of the high and normal recharge controls have to be adjusted until the average recharge that has been obtained from the ^{14}C model, is in agreement with the estimate derived from the chloride mass balance (CMB method). However, the latter estimates also proved to be unreliable because it depends on the reliability of the chloride input from the rainfall. This has lead to a closer scrutiny and a more reliable estimation of the chloride input from the rainfall.
- The chloride concentrations of the rainfall has been derived indirectly from the flows of various springs that could be simulated according to the average rainfall of a characteristic period in relation to the recharge area. The recharge area is usually delineated according to geological boundaries and piezometric drainage maps. However, even a wrong drainage area to derive the effective monthly recharge coefficients, could initially be used, as the recharge coefficients should be the same as that derived from the CMB ratio. Thus the best match between the two sets of chloride values of the spring water would yield the most likely concentration of the chloride of the rainfall. Any discrepancies between the two sets of chloride values would mean that the recharge area has to be adjusted. The entire procedure presupposes that the measured chloride concentrations of the spring water are reliable and represent the natural outcome and that no contamination has occurred.
- The ^{14}C simulations have indicated that the residence time of water in the aquifer is much less than had originally been claimed based on the inferred ^{14}C age of the groundwater. The only exception has been the groundwater from the Sishen quarry, which, according to the ^{14}C model, has indicated the presence of a component of real old water.
- A relationship between the chloride or bicarbonate concentrations has been established that enables reasonable quantitative determination of the average recharge of dolomitic aquifers from the bicarbonate concentrations. Similar application in other aquifers should still be evaluated for other aquifer types.
- Reliable simulation of the impact of pollution of two dolomite aquifers, according to the recharge and flow characteristics that have been derived from the ^{14}C model, has been achieved. From this the input pulse of the pollution could be reconstructed by inverse modelling. The pollution could thereby be linked to the probable source of the contamination, e.g. in the case of Turffontein eye.

- The sustained impact of pollution and the likely effect of remedial measures could be simulated by the ^{14}C model and it has indicated that the contamination could persist for several decades even if the pollutant source could be cut-off completely.
- The empirical ^{14}C model has clearly indicated that there is a lag in the response of the ^{14}C, which is partly ascribed to the retention of some of the recharge in the unsaturated zone, but in some instances a significant lag had to be introduced that is indicative of admixture of water contained in the aquifer matrix. This finding is in accordance with a similar conclusion in a recent publication of Shapiro (2001) that has indicated through tracer studies that the matrix-water is an active part of the dynamical flow in the aquifer.
- In the case of tritium similar but larger lags have been observed, which have indicated there is a large reservoir of water molecules in the unsaturated zone overlying an aquifer, which dilutes the incoming tritium pulse. Hence the input of ^{14}C into the unsaturated zone occurs at a greater depth, i.e. at the root zone of the vegetation, and is therefore less diluted than the tritium. In the case of CFC being used as tracer its input occurs at the interface between the unsaturated and saturated aquifer regimes. This results in the CFC having shorter lag times in the model. However, as the CFC simulation has been based on a single measurement, it merely provided a qualitative indication that the spring water is of recent origin and that it is also an acceptable tracer to use in dolomitic aquifers.
- The successful simulation of the time variant ^{14}C values from the input concentrations of the rainfall recharge has convincingly proved that there is no need to frequently sample and analyse the spring water and it could even be abandoned. Selective analysis at some of the key springs could be continued at intervals of about two years.
- Simulation by the FEFLOW model has been almost as successful as the conceptual model presented in this paper but should be extended to a 3-dimensional model.

Section 14. Research results

1. The study has made a major contribution to the understanding of the hydrological processes that control the recharge and mixing of water in dolomitic aquifers. The study has also provided improved estimates of the recharge of these aquifers and of their relative storages in relation to the average annual recharge. The study has furthermore yielded new methods to assess the groundwater potential of the dolomitic aquifers and have proved that these aquifers are essentially similar as regards the recharge processes, but that the scale of parameter values could differ significantly.
2. The study has provided for the first time an insight into the mixing of recent recharge with the deeper water that is stored in the aquifers, which has been confirmed by a FEFLOW model of a section of the aquifer. According to the residence times the volumes of water in storage could be expressed as multiples of the average annual recharge.
3. In accordance with findings of Shapiro (2001), it seems that water contained in the aquifer matrix makes a contribution to the intermixing of groundwater, which is important in pollution studies but its potential for utilization still is negligible.
4. The FEFLOW, and to a lesser extent, the Excel model has contributed to a better understanding of tracer responses in these aquifers. The FEFLOW simulations should be extended to a full 3-dimensional model of at least a few of the dolomitic aquifers.

5. A significant result is that the monthly recharge values that have been derived from the ^{14}C modelling (and the simulations of the spring flows by incorporation of a low and high threshold rainfall), could be reduced to a binomial or exponential equation in relation to the average rainfall over a characteristic period. It could provide the key to more effective assessment planning and management of these and other aquifers. It could furthermore provide the basis for determining the groundwater reserve of all aquifers in a consistent and hydrological acceptable way.
6. The outcome of the study can instigate new studies on the water quality of these aquifers and their role to assess the extent of pollution.
7. The bicarbonate of the dolomitic aquifers could provide another means of quantifying the recharge, although the estimates would be more variable than the CMB method. The indication is that inflated bicarbonate concentrations could also be an indicator of occurrences of pollution in these aquifers.
8. The use of bicarbonate concentrations to estimate the recharge in other aquifers still has to be pursued as it entails a comprehensive study.

Section 15. Recommendations

The following specific recommendations are made:

i) More extensive and reliable sampling and measurement of the chloride of the rainfall at different localities should improve estimations of the recharge according to the CMB method for the entire country. Integrated monthly samples would be adequate for most purposes. However, more intensive sampling of individual rain events at an inland station, e.g. Pretoria, and one in a more arid region, e.g. Kuruman and in the TMG aquifer region, is required to determine variations of the chloride in relation to the daily intensity of the rainfall. The dry deposition of chloride could hopefully be derived according to the relationship shown in Figure 24.

    All available data on the chloride of rainfall, e.g. monitoring data that have been accumulated by FORESTEK in the afforested mountainous areas, should be obtained for a combined scrutiny and extension of the regional distribution of the chloride input over the RSA.

    The new method, based on the flow of the springs and the measured chloride concentrations of the spring flows, should be reassessed and compared to the rain monitored chloride concentrations to obtain the best average chloride values for the springs. From the latter, the effective recharge area could be accurately inferred according to the relationship shown in Eq. 3.

    Continued analyses of the chemical ingredients of the major springs should be carried out at least once a year before the start of the new hydrological year, not only to improve the recharge estimates by the CMB method, but to indicate occurrences of pollution in these aquifer systems.

ii) Having obtained more reliable estimates of the recharge coefficients by the CMB method, the relationship between the bicarbonate and the recharge has to be refined. The bicarbonate method should also be checked for different types of aquifers, e.g. the Karoo Formations, coastal aquifers, basalt and quartzitic aquifers of the TMG and Transvaal sequences.

iii) There is no real need for continued monitoring of the ^{14}C of those dolomitic springs for which reasonable measurements have been obtained, but additional analyses every 5 years could be used to check the predicted responses according to the present ^{14}C model. There is no need to continue the measurement of tritium and CFC in view of their limited application and less quantifiable interpretations of the recharge/aquifer parameters.

iv) The use of a simple rainfall-recharge relationship without having to incorporate the ineffective rainfall according to the threshold values that have to be exceeded, provides the key to implementing it as the basis to determine the reserve and allocation permits on a sound hydrological basis. The groundwater levels also correspond to the moving average rainfall over the characteristic period and would therefore ensure a consistent adjustment of water allocations if the average rainfall over the characteristic period declines below a set minimum. The effect of abstraction is incorporated as an equivalent negative rainfall to be abstracted from the moving average rainfall (MA method), which enables projections of the future response of the aquifer to be made in a very simple manner. This approach would enable any local groundwater controlling body to manage their groundwater resources effectively.

v) The FEFLOW model should be extended to a 3-dimensional simulation of ^{14}C of the Grootfontein-Molopo, Rietvlei, Turffontein and Renosterfontein dolomitic aquifers to verify the empirical ^{14}C conceptual model, but more importantly, to simulate transport and mixing of pollution in aquifers like Gerrit Minnebron.

vi) The study would significantly contribute towards improving the knowledge and understanding of groundwater of almost the entire spectrum of the population of South Africa. The project has provided new perspectives on the occurrences, the potential and limitations of groundwater resources from which the highest levels of management could benefit and refine policies to protect and secure sustainable utilization of the dolomitic aquifers, as well as extending some of the methods to other aquifers. The study would prove to be a key contribution to the curricula of universities and colleges teaching groundwater hydrology. Hopefully even at school levels pupils would benefit from information that has been produced in the study.

vii) Application of the ^{14}C model and the use of chloride to determine the recharge would have to be demonstrated to selective groups of the groundwater industry.

viii) Wide distribution of the report is recommended in view of it providing a much clearer understanding and validation of the hydrological rationale that governs the occurrence and estimation of groundwater resources. The results and outcome of the project also provide essential links towards the provision of a blueprint for policy-making and effective practical management of the groundwater resources of South Africa and elsewhere in the world.

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