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.

- 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.
- 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.