EVALUATION OF THE APPLICATION OF NATURAL ISOTOPES IN THE IDENTIFICATION OF THE DOMINANT STREAMFLOW GENERATION MECHANISMS IN TMG CATCHMENTS

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Evaluation of the application of natural isotopes in the identification of the dominant streamflow generation mechanisms in TMG catchments

Report to the

WATER RESEARCH COMMISSION

by

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Executive Summary

Background and Motivation

An increased focus on the development and use of groundwater resources means that a better understanding of the functioning of groundwater systems is required in order to ensure that groundwater development occurs in a sustainable manner. Among the aquifers intended for further development are the Table Mountain Group (TMG) aquifers of the Western Cape and Eastern Cape. The National Water Act (Act no. 36 of 1998) requires the implementation of Resource Directed Measures that among other things first allocates water to the natural environment and basic human needs, before other uses may be allocated. If the development of aquifers such as the Table Mountain Group aquifer is to take place in a manner that does not have a detrimental impact on ecosystems that depend on the streams that have their origin in the mountainous headlands, an improved understanding of the processes of groundwater recharge and streamflow generation is required (Roets, 2001). Only in this way can an understanding be developed of the link between groundwater and the continued flow of mountain streams. The Stream Flow Reduction Activities (SFRA) Programme (Ad Hoc meeting of 27 March 2001) has identified the need for "a better understanding of the lateral movement of water and the connection between groundwater and surface water".

Project Aims and Objectives

This project aims to improve the process hydrological modelling in headwater catchments based on a proper understanding of flow paths, residence time and reservoir size. This would help to develop a predictive capacity for TMG aquifers based on an understanding of flow mechanisms and flow paths in headwater catchments. This report represents the output of a preliminary phase to an envisaged field research study that have these objectives in mind. As such this report contains recommendations on how research as part of a field research study should proceed.

Methodology

Research was aimed at the development of a sound knowledge base from which detailed field research could be initiated. Available knowledge on the use of isotope and geochemical techniques in streamflow hydrograph separation was synthesised through the review of literature and interaction with international and local researchers. At the same time a research

site was selected and a research strategy developed for detailed field research to test the suitability of isotope and geochemical hydrograph separation techniques under South African conditions.

The review of existing literature focused on the use of isotope and geochemical techniques for the separation of streamflow into its relative components. Results from studies where isotope and geochemical techniques have been applied, have consistently found that old water (groundwater and inter-flow) makes a bigger contribution to stormflow than calculated by graphical means (Sklash and Farvolden, 1979, Pearce, et al., 1986, Rickey, et al., 1998, and others).

Isotope streamflow separation has been applied to the study of the contribution that old water makes to streamflow during storm events (Sklash and Farvolden, 1979, Sklash, et al., 1986, Ladouche, et al., 2001), the calculation of aquifer reservoir size and water residence time in aquifers (Pearce, et al., 1986, Midgley and Scott, 1994, Frederickson and Criss, 1999, and Asano, et al., 2002).

The selection of the Zachariashoek Research catchments as a possible site for further field research was based on practical considerations, including the presence of research infrastructure and the availability of historical data, as well as the fact that the catchments are dominated by rocks of the Table Mountain Group sandstones, which would make the results of streamflow research relevant to ongoing research on the feasibility of groundwater abstraction from the Table Mountain Group aquifer and its impact on ecosystems.

In order to enable the design of the research strategy for the Zachariashoek research catchments some of the historical data available for the site were analysed and interpreted. This included rainfall data, and streamflow data from the five weirs in the three catchments.

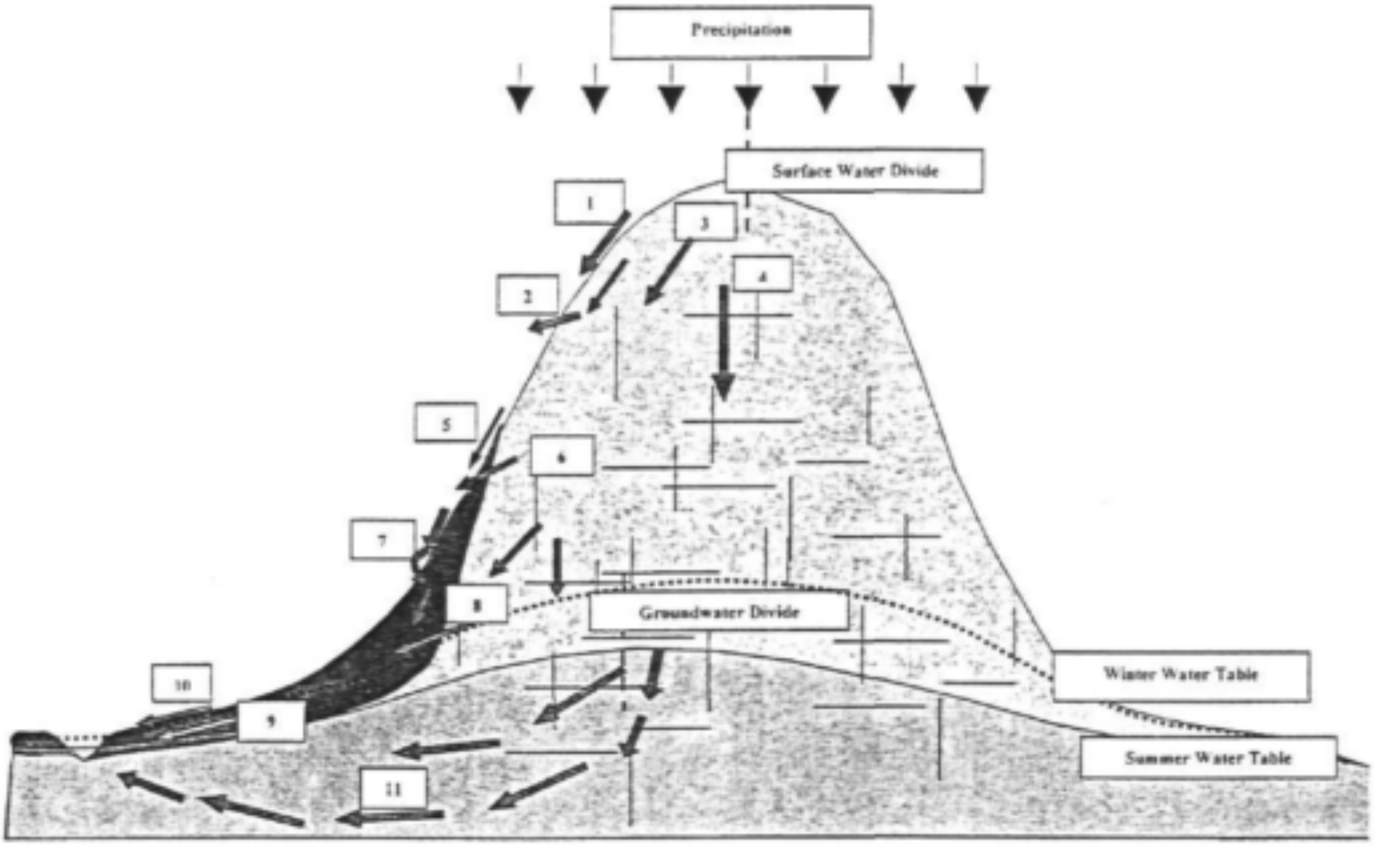
Discussion and Conclusions

International experience has shown that the application of isotope and geochemical techniques can provide valuable insight in the breakdown of stormflow into its different components. In this way these techniques have the potential to contribute significantly to the understanding of the hydrological processes in humid headwater catchments, when used in conjunction with hydrological flow analysis.

The Zachariashoek research catchments were identified as ideal for the testing of the applicability of these techniques under South African conditions. From the analysis of historical data for the three Zachariashoek research catchments it was found that the catchments have a high quickflow response and a small low flow contribution to the total flow. From this it is concluded that these headwater catchments have relatively little storage capacity that contributes to sustained flow. It was also found that the lower nested catchments (Zachariashoek and Kasteelkloof) have more low flow, and better-sustained low flow than the upper portions of these catchments.

From the historical data analysis it appears that the very low flow volumes in the driest months combined with low summer yields relative to rainfall, that there is a limited supply of streamflow from "delayed flow" sources – which might be assumed to be true groundwater discharge. This is in contrast to the Jonkershoek catchments that have a greater proportion of "delayed flow". Based on the catchment characteristics noted during the flow analysis, it is concluded that the Zachariashoek catchment and one of the other two catchments (preferably the Kasteelkloof catchment) be selected for field study.

Present understanding on the dominant flow processes in TMG headwater catchments is represented by the following figure and table (section 4.5).



Conceptual model of flow processes in TMG headwater catchments.

Description of flow processes in TMG catchments.

No.	Description
1	Surface runoff from rock outcrop on steep slopes.
2	Emergence of spring water and seepage from fractured rock.
3	Lateral induced flow in fractured rock due to hard-rock fracture orientation.
4	Vertical recharge flow in fractured rock due to fracture orientation
5	Local surface runoff from soil profile
6	Preferential flow in soil profile due to: ○ macropore structures ○ groundwater ridging in perched water table
7	Re-infiltration of surface water into soil profile in shallower slopes with a deeper soil profile.
8	Re-emergence of lateral fractured flow component into soil profile.
9	Preferential flow in soil profile
10	Local surface runoff as in 5.
11	Groundwater aquifer lateral flow due to gradient of phreatic surface and flow paths in the groundwater system.

The research team believes that detailed field research would make a valuable contribution to the understanding and management of fragile headwater catchments. The detailed research plan that has been developed for the Zachariashoek research catchments would provide answers and/or insight to the following questions:

- The different flowpaths that water follows to streams?
- The length of these flow paths (travel times)?
- The size of the groundwater reservoir?
- Average annual groundwater recharge in these catchments?
- The volume of groundwater that can be abstracted in a sustainable manner?

Answers to these questions are especially relevant in Table Mountain Group dominated catchments where groundwater abstraction is being considered. The ecological importance of mountain fynbos and the perceived sensitivity of mountain streams to groundwater abstraction means that many of these questions will have to be answered before large-scale groundwater abstraction from the TMG aquifer can be considered (Roets, 2001)

Research is underway to provide answers on the feasibility of groundwater abstraction from the TMG aquifer and its likely ecological impact. The processes of streamflow generation however will not be considered in these studies. The TMG specific nature of the research also means that its application in other catchments is limited.

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1. Introduction

1.1. Background

Research into the processes of streamflow generation in headwater catchments has in recent years generated renewed interest internationally, with a large number of publications being generated on the topic (e.g. Gburek and Folmar, 1999, Ribolzi, et al., 2000, and Ladouche, et al., 2001). The review of South African environmental and water legislation has at the same time fuelled interest in the functioning of South African headwater hydrological systems (Kelbe, et al., 1992, Lorentz and Esprey, 1998, and Lorentz, 2001). A lot of the insight and data generated by current hydrological research have led to a questioning of conventional models of streamflow generation that see overland flow as the dominant path that rainwater follow to streams (Bonell, et al., 1990, McDonnell, 1990, and Buttle, 2000).

In South Africa the need for a more comprehensive understanding of streamflow generation processes is driven by the need to allocate a ecological reserve in hydrological systems (Xu, et al., 2001). Understanding the processes of streamflow generation offers insight into the interaction between groundwater and surface water. A need therefore exists for conceptual models that more accurately reflect natural processes. Our understanding of surface water-groundwater systems is limited, especially in the headwater catchments where many streams and rivers start.

A detailed study has been made of the flow processes involved in a catchment underlain by sedimentary rocks of the Molteno Formation in the north Eastern Cape (Lorentz and Espey, 1998, Lorentz, 2001, and Lorentz, 2002). Elsewhere, however attempts at developing a rule-based model of hydrological processes in headwater catchments have been frustrated by a lack of field data. This emphasises the need for continued research on hydrological processes that characterise South African catchments.

1.2. Problem Statement

Rapid population growth, increased industrialisation and the expansion of agriculture are placing increased pressure on South Africa's water resources. As a result new sources of supply are being evaluated, including the increased pumping of groundwater systems such as the Table

Mountain Group (TMG) aquifer. The National Water Act (Act no. 36 of 1998) requires the implementation of Resource Directed Measures that among other things first allocates water to the natural environment and basic human needs, before other uses may be allocated. If the development of aquifers such as the Table Mountain Group aquifer is to take place in a manner that do not have a detrimental impact on ecosystems that depend on the streams that have their origin in the mountainous headlands, an improved understanding of the processes of groundwater recharge and streamflow generation are required. Only in this way can an understanding be developed of the link between groundwater and the continued flow of mountain streams.

In order to predict possible impacts, the Streamflow Reduction Activities (SFRAs) Programme has identified as vital to the sustainable management of water resources, the need for "a better understanding of the lateral movement of water in catchments and the connection between surface water and groundwater" (ad hoc meeting held on the 27th of March 2001). The objectives of this project have been developed in order to broaden the hydrological understanding of processes in catchments, with an emphasis on the flow path of water to headwater streams and the impacts that may be expected from groundwater abstraction.

The National Water Act requires that the ecological reserve be set for water resources, and recognizes the continuity of hydrological systems. With respect to groundwater, therefore, the effects of exploitation on surface water bodies have to be estimated. This pre-supposes that there is an understanding of the nature of the inter-connection of surface and groundwater systems, and that the inter-connection can be quantified. This understanding is limited in most groundwater systems. The National Water Act also requires the formulation of water resource strategies. The development of these strategies requires a thorough understanding of the functioning of the systems being managed. From the perspective of administering the country's water resources as prescribed by the legislation, it is important:

- to develop this understanding for all the important aquifer systems in South Africa,
- to develop techniques that will assist in building up such an understanding and
- to develop tools or procedures to aid the administrators in developing policy and in responding constructively to applications for water use licences.

This project addresses the above needs. It aims to develop an understanding of the interaction between the different components of the hydrological cycle through the research of hydrological processes in a TMG catchment of the South-Western Cape, in terms of sources of water, flow paths and residence times. The literature review conducted during this project and the preliminary analysis done on the Zachariashoek research catchments should assist future research into the development of secondary decision making tools.

1.3. Research Objectives

The project proposed to develop an improved conceptual model of streamflow generation in headwater streams by establishing the contribution that groundwater makes to streamflow during both storm events and baseflow periods. In this way the research would help to:

- Improve the basis for process hydrological modelling in headwater catchments based on a proper understanding of flow paths, residence times and reservoir sizes; and
- Develop a predictive capability for hydrological systems, based on an understanding of flow mechanisms and flow paths in headwater catchments.

Interest in the development of the TMG aquifer and the need to understand the response of this aquifer to large-scale pumping offers the opportunity for the products of streamflow generation research to be used in building sound quantitative models that could be applied in the management of water resources in the Table Mountain Group system. The need for such research follows from the fact that presently limited knowledge exists on the characteristics of flow (Rosewarne, 2001, and Woodford, 2001), the rates of recharge (Parsons, 2001), the residence time of water and the volume of storage in the TMG system (Weaver and Talma, 2000), and on how flow is generated in streams in TMG dominated catchments (Midgeley and Scott, 1994). Increasing water stress in the Western Cape means that there are increased demands for abstraction from the TMG aquifer and for developing an understanding of the impact that this may have on the environment. This is especially relevant with respect to the setting of the ecological reserve and the Resource Quality Objectives.

1.4. Methodology

An overview of current practice and understanding on the use of isotope and geochemical hydrograph separation techniques was obtained through the review of local and international published literature. This study was further informed through consultation and discussion with international and local researchers. This included the hosting of a catchment hydrology workshop with local scientists and researchers, which was led by Professor Jeff McDonnell, of

Oregon State University who serves as president of the International Commission on Tracers. A list of participants in this one-day workshop is presented in Appendix 1. Further discussions on the application of isotope and geochemical techniques were held during planning meetings and a field visit to the Zachariashoek research catchments. The insight gained through the review of published literature and the input of Professor McDonnell was used to develop a strategy and workplan for detailed field research.

The Zachariashoek research catchments near Stellenbosch were identified as suitable for the kind of research that is envisaged for the following reasons:

1. Its close proximity to Stellenbosch makes access easy and relatively affordable.
2. A substantial monitoring infrastructure already exists at the Zachariashoek research site. This includes:
   - streamflow gauging stations, and
   - boreholes
3. The research catchments are largely in an undisturbed state and covered in indigenous fynbos vegetation, like the bulk of the mountainous TMG.
4. Detailed and at times continuous data records exist (1960's – 1991) of:
   - stream flow,
   - groundwater levels and
   - precipitation
5. The Department of Water Affairs and Forestry supports research at the site. During two site visits the research merits of the site was discussed, and agreement reached on the infrastructure improvements and repairs that would be necessary and ways in which the department could assist in the repair of damaged infrastructure.
6. The proximity to the Wemmershoek dam means that results would be relevant and applicable to managers at that facility. This may provide an additional source of research funding, and may provide additional meteorological data applicable to the area.
7. The complex and apparently deep nature of South African hydrological systems means that local research needs to look at a larger scale than similar studies in other parts of the world. The Zachariashoek research catchments provide an opportunity for such research.

8. Research in larger catchments like those at Zachariashoek would make results more relevant for application to other catchments and to management of the complete TMG system.

1.5. Report Structure

This report presents a synthesis of available knowledge on the use of isotope and geochemical techniques in understanding streamflow generation and presents a research strategy and workplan for the testing of current understanding and techniques under South African conditions.

Section 2 of the report is devoted to the literature review. Section 3 gives a description of the Zachariashoek study site, while Section 4 presents an analysis and interpretation of some of the historical data available for the study site and presents a conceptual model on present understanding of flow processes in TMG dominated headwater catchments. Section 5 contains a discussion on the useful application of this research and the way forward.

2. Literature Review - Methods in Streamflow generation analysis

2.1. Introduction

Understanding the processes by which water drains through catchments and sustains flow in rivers is of fundamental importance to hydrologists. These processes are however complicated by the large number of variables that may influence them. In order to simplify research it is generally assumed that under natural conditions each river and stream receives water only from its own drainage basin or catchment area. Input can then be interpreted as being represented only by precipitation, while evaporation and streamflow represent outflows. It is further sometimes assumed by surface hydrologists that the underlying formations do not allow the movement of significant amounts of water from the catchment.

Streamflow varies over time, with periods of high flow occurring in association with precipitation or snow melt events. Streams tend to respond rapidly to precipitation events, and the flow generated in this way is referred to as storm-flow or quick-flow. Water also follows a much slower path to the stream. This is the process through which flow in streams is sustained through most of the year in most systems. The flow that occurs while the system experiences little or no precipitation input is commonly referred to as baseflow (Ward and Robinson, 1990).

2.2. Graphical Hydrograph Separation

The separation of a stream hydrograph into its components is based on the assumption that the different components of flow arrive at the stream at different intervals. Overland flow would arrive most rapidly, through-flow next, and groundwater flow at the slowest rate. The processes through which this flow takes place, and the proportions that each contribute to streamflow remains an area of scientific debate (McDonnell and Buttle, 1996, and Kendall, et al., 1999).

Generally in graphical hydrograph separation an arbitrary separation is made between quick-flow and slow-flow. A widely used approach is that proposed by Hewlett and Hibbert (1967) in which quick-flow is separated from delayed flow by a line of constant slope (0.0472 mm/day) projected from the beginning of a stream rise to the point where it intersects the falling limb of the hydrograph. This value was chosen because it was greater than the normal diurnal fluctuation of flow, gave a relatively short time base to the largest single-peaked hydrographs and permitted large storms separated by a period of about three days to be calculated as separate events (Ward and Robinson, 1989) (see Figure 1).

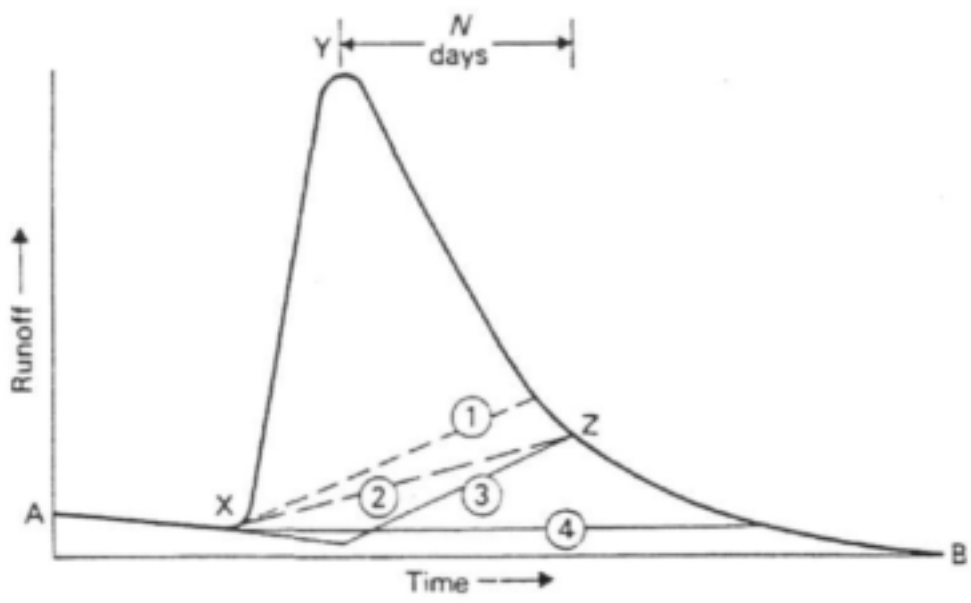

Figure 1: Methods of graphical hydrograph separation. (Ward and Robinson, 1989)

Other separation techniques separate quickflow and baseflow by drawing a straight line from the sharp break of slope X (Figure 1) where discharge begins to increase to a chosen point (Z) on the recession limb of the hydrograph. Point Z may be located at the point of greatest curvature near the lower end of the recession limb (line 1) or at a given time interval after the occurrence of peak flow (line 2). The time interval may be determined from hydrograph inspection or from a simple empirical equation:

$$N = A^{0.2}$$

where N is in days and A is the drainage area in square miles.

Alternatively the pre-storm baseflow recession curve (AX) may be projected forward in a straight line to an arbitrarily chosen point Z (line 3). The simplest approximation is that of a horizontal line drawn from point X to its intersection with the recession limb (line 4).

Hydrometric methods alone, however, fail to adequately explain stream chemistry during storm runoff events. The main failing of the hydrometric method is that although they quantify discharge into various components, they do not determine exactly where that water comes from.

2.3. Isotope Techniques

Background to Environmental Isotopes

Environmental isotopes routinely contribute to a hydrogeologist's understanding of the processes taking place in the water cycle. Meteoric processes, for instance, modify the stable isotopic composition of water, and so the recharge waters in a particular environment will have a characteristic isotopic signature. This signature serves as a natural tracer for the area of groundwater recharge. On the other hand, radioisotopes decay, providing a measure of circulation time (age) of the water.

The isotopes of oxygen and hydrogen have found the widest application in hydrology studies. These elements form part of the water molecule, which makes them ideal for tracing water movement. The evaporation of water from water bodies produces a water vapour that is depleted in the heavier isotopes (^{18}O and ^{2}H) relative to the remaining water. As regional or continental atmospheric circulation systems move the water vapour inland, and as the process of condensation and precipitation is repeated, rain or snow become characterized by low concentrations of these isotopes.

The plotting of the observed global oxygen and hydrogen isotope concentrations in precipitation produces a line known as the global meteoric water line. Values however differ for different parts of the world. Variation in the equation for the meteoric line at a specific location is a function of its climate, geographic location and the source region of the evaporation. Diamond and Harris (1997) found that Western Cape meteoric water defines a meteoric water line with the approximate equation $\delta D = 6.1\delta^{18}O + 8.6$. The isotope composition of water that recharges groundwater in the Western Cape should approximate the weighted annual δD and $\delta^{18}O$ values.

Water with an isotopic composition that falls on the meteoric water line is assumed to have originated from the atmosphere and to be unaffected by other isotopic processes. Deviations from the meteoric water line result from other isotopic processes. In most cases these processes affect the relationship between δD and $\delta^{18}O$ in such a unique way that the position of the data points can help to identify the process. Two of the more commonly observed processes are evaporation from open water bodies and isotopic exchange between minerals and groundwater in deep, basinal flow or geothermal systems (Domenico and Schwartz, 1990).

Stable environmental isotopes are measured as the ratio of the two most abundant isotopes of a given element. This is reported in delta (δ) notation as permil (‰), which represents the deviation from a standard. The following general equation is used to calculate the deviation of the isotope ratios from a standard:

$$\delta = (R_{sample} - R_{standard}/R_{standard}) \times 1000$$

The deuterium and oxygen-18 content of water are usually measured with respect to the SMOW (Standard Mean Ocean Water) standard.

Oxygen and Hydrogen

The behaviour of certain isotopes are conservative, and do not decay or react with other minerals. The conservative nature of oxygen-18 and deuterium and the fact that they represent an inherent component of the water molecule, makes possible the tracing of water movement through watersheds. The isotope composition of the water changes only with mixing; which allows the determination of the contribution of end members of a mixed sample.

Hydrograph separation using stable environmental isotopes has been widely applied in hydrological process studies (e.g., Pearce, et al., 1986, Sklash, et al., 1986, Bonell, et al., 1990, McDonnell, et al, 1990). The basis of this method is temporal variations in the isotopic composition of precipitation, resulting in the isotope composition of the event water differing from the composition of the water already in the catchment (Genereux and Hooper, 1998). In numerous studies, stable isotopes have been used as tracers to infer the relative contributions to runoff from soil water, groundwater, storm precipitation, and snowmelt.

Hydrograph separation through the use of isotopes utilise the isotopically distinct character of water sources to apportion the contribution of two or more sources to stream runoff. The differentiation in stream flow contribution is based on the time source component, where:

1. water produced during a rain of snow-melt event is referred to as new or event water, and
2. soil water or groundwater already in the catchment at the start of the event is referred to as old water or pre-event water.

It should be remembered that a two-component isotopic hydrograph separation yields the proportions of event and pre-event water in a stream. The processes of storm runoff generation require interpretation and additional methods.

The storm hydrograph is separated into storm water (N) and pre-storm water (O) components using a combination of water and isotopic mass balance equations (Sklash et al., 1986) to yield:

$$Q_O = Q_T\ [\ \delta t - \delta_N/\delta_O - \delta_N]$$

and

$$Q_N = Q_T - Q_O$$

Where Q is discharge, δ expresses the isotopic concentration, and the subscripts T, N, and O refer to total, new and old waters respectively.

A common approach is to bulk sample rain and determine its isotopic content as an estimate of δN with the result reported as 'weighted average' value. This method assumes that any temporal variability of δN during a storm randomly occurs around the weighted average value. Significant error can occur when this assumption is not met, especially when the rain signature trends away or across the weighted average line, as shown by McDonnell et al. (1990). An alternative is to continuously adjust δN during the course of the storm for the period from the commencement of the storm up to the time of taking each stream sample. In this way future rain does not influence the calculations.

Requirements and assumptions in hydrograph separation

Oxygen and hydrogen isotopes may be used to separate a hydrograph if the difference in the isotopic compositions of event and pre-event waters is large relative to the isotopic variability within each component and the analytical uncertainty associated with the isotopic analyses. According to Sklash and Farvolden, (1979), successful isotopic hydrograph separation requires that:

1. The isotopic content of the event composition is significantly different from that of the pre-event component.
2. The event component maintains a constant isotopic content.

3. The groundwater and vadose water is isotopically similar or vadose water makes a negligible contribution to runoff.
4. Surface storage contributes minimally to the runoff event.

Hydrograph separation often fails because of the similarity in isotopic composition of the event water and the pre-event waters, or because of significant variability during the event. The major strength of the technique is that stream isotope data offer a watershed-scale signal that is linked to hydrologic pathways.

Studies conducted through the use of isotope techniques have consistently found that pre-event water contributes a large fraction to storm flow. This finding together with rapid response of streamflow to storm rainfall has increased uncertainty about the mechanism through which pre-event water is discharged to streams so shortly after the onset of an event.

Tritium

Kennedy et al. (1986) describes the use of tritium in a hydrograph separation study. The rationale used is similar to that in the use of the stable isotopes of oxygen and hydrogen. The technique allows the contributions of old and new water to be determined through end-member analysis. Distinctly different old and new water tritium values are required for runoff hydrograph separation. In small catchments where the average residence time of the old water is on the order of months, the old and new water tritium concentrations are not likely to be distinguishable (Kendall, et al., 1992). However, in larger catchments with longer residence times, old and new waters may be distinctive as a result of the gradual decline in precipitation tritium values.

Tritium measurements are frequently used to calculate recharge rates, rates or directions of subsurface flow and residence time (Kendal, et al., 1992). For these purposes, the seasonal, yearly and spatial variations in tritium content of precipitation must be accurately assessed. This is difficult to do because of the limited data on background levels available especially before the 1960s.

Other Tracer Isotopes

Kendal et al. (1992) discusses alternative, independent isotopic methods for apportioning stream runoff into water flowing along various subsurface paths. Some of the tracer isotopes that have been used include: radon-222 (e.g. Genereux and Hemond, 1990), beryllium-7 and sulphur 35 (Cooper et al., 1991), carbon-13 (Kendal et al. 1992); and strontium-87 (Bullen and Kendal, 1991). These isotopic methods can compliment ^{18}O and ^{2}H investigations or replace them where problematic. Reactive solute isotopes such as ^{13}C, ^{34}S and ^{87}Sr can provide valuable information about water flow paths. Water flowing along mineralogically distinctive horizons are sometimes distinctively labelled by their chemical composition and by the isotopic compositions of solute isotopes like ^{13}C, ^{87}Sr, ^{34}S, ^{15}N, etc.

The limitations of these methods are that they remain relatively untested, require complicated sampling procedures, with commercial analysis often restricted to only a hand full of labs world-wide.

Sampling Considerations

Though the use of isotope chemistry in hydrograph separation has added a lot to our understanding of hydrological processes, its general application is complicated by its variability. The following section highlights some of the problems or difficulties that may arise during water sampling.

Soil Water

Soil water samples can be obtained from coring and subsequent centrifugal or azeotropic distillation, tension or suction lysimeters, and zero-tension lysimeters. There are indications that the $\delta^{18}O$ content of soil water sampled from intact cores by azeotropic distillation is more negative than water obtained from tension lysimeters (Hemmen, 1990 as referred to by Buttle, 2000). This is attributed to the inability of tension lysimeters to sample more strongly bound (and isotopically more negative) water held in micropores (Hemmen, 1990).

In sampling soil water it is important to note that isotopic exchange with most minerals is extremely slow under normal ambient conditions (Kennedy, et al., 1986). The work of Kennedy, et al. (1986) showed that no detectable isotopic exchange between soil minerals and interstitial water occurred over a 19-day period. It was further found that the exchange of atmospheric moisture with moisture in surficial soils occurs on a time scale similar to that between storms. The many factors that affect such exchange made it difficult to estimate the magnitude of this on the isotopic composition of soil water.

Many studies also assume that the contributions of water from the unsaturated zone to stream flow is negligible. Kennedy et al. (1986) notes that a sandy loam that drains to field capacity can contain 20-25% soil water. The water in near-surface soil will represent some mixture of water from previous precipitation events, as modified by evaporation-related processes and perhaps by interaction with atmospheric water vapour. When rain falls on a soil at or near field capacity, it can cause the displacement of the previously stored soil water into the channel network where it would be mixed with channel precipitation, any overland flow and displaced groundwater.

Base flow

Many hydrograph separation studies assume that groundwater and baseflow are characterised by a single isotopic content. Because rainfall isotopic compositions can be extremely variable, it could be that the isotopic composition of baseflow will change to some extent with time and discharge. However, the deeper the vadose zone from which the water comes and the longer the groundwater has been stored, the greater the probability that dispersion and mixing effects will have integrated the isotopic composition of infiltrating rain from many rainfall events (Kendall, et al., 1992).

Precipitation

Hydrograph separation requires that rainfall during an event be characterised by a single isotopic content, or that variations in the isotopic content can be documented. Rainfall intensity and isotopic composition are quite variable within an individual storm. Because gentle to moderate-intensity rain may infiltrate completely, whereas high-intensity rainfall with a different isotopic composition may run off hillslopes quite rapidly, the composition of surface stormflow may not match that of the average isotopic composition of the rain. Thus, computation of the relative amounts of rainfall and pre-storm water in storm runoff, using the average isotopic composition of all the rainfall, can yield faulty results. Such shedding of higher-intensity rainfall can also cause a difference between the isotopic composition of groundwater and the average composition of rainfall in an area.

Gonfiantini et al. (2000) summarises the variations in the isotopic composition of precipitation relative to the concentration of the heavier isotopes as follows:

1. Seasonal variations in temperate and polar zones, with winter precipitation depleted and summer precipitation enriched;

2. Variations correlated with the precipitation amount in tropical zones, with heavy rains depleted and light rains enriched;
3. Variations correlated with the altitude, with precipitation at high altitude depleted and at low altitude enriched;
4. Heavy isotope enrichment due to partial evaporation of raindrops during fall; this effect is particularly noticeable for light rains in arid zones.

2.4. Mechanisms of groundwater discharge

A number of theories have been developed to explain the rapid response of small catchments and the apparent dominance of groundwater in such streams. Some of the theories advanced by authors include Macropore flow by Mosley (1979), Capillary fringe response by Gilham (1984), Groundwater ridging by Sklash and Farvolden (1979), and Piston displacement of soil water (Kennedy, et al., 1986). None of these mechanisms however succeed in explaining the streamflow generation mechanisms for all environments (McDonnell and Buttle, 1996) and may only be applicable to sites of a particular pedologic, geologic, topographic, climatic and vegetative condition. At this stage it is not clear which method or combinations of methods may apply to South African conditions. It is however noted that the TMG dominated headwater catchments of the Western Cape do show similarities with the Maimai M8 research catchment described and studied among others by Pearce et al. (1986). In an analysis of the water discharge to the Maimai stream McDonnell (1990) show macropore flow to be an important mechanism in the delivery of old water to the stream channel during storm events. The validity of this mechanism in South African headwater catchments will have to be tested using some of the tools outlined in this document.

2.5. Geochemical Hydrograph Separation

Geochemical hydrograph separation is based on the principle that water can pick up a unique chemical signature depending on its source area. This can then be used to determine the relative amounts of stream water that derive from different sources. The fundamental difference between a non-reactive isotope of water and a chemical tracer of water is that the isotopic content changes only as a result of mixing, while the chemical composition changes as a result of interaction with the soil or bedrock and residence time in a certain aquifer or rock type.

In general isotopes trace the source of water, while chemicals trace the flow paths of water. Geochemical tracers may thus be used to separate streamflow into runoff components according to their flow paths, independent of their origin (old vs. new) and degree of mixing (soil water vs. groundwater) (Kennedy, et al., 1986). The exact definition of the flow paths depends on the source and dissolution rates of the chemical tracer used for separation. In order to avoid speculative interpretation and erroneous conclusions based on chemical hydrograph separation, the soil kinetics of the geochemical tracer must be investigated.

Some soil constituents are slightly, but rapidly soluble (Kennedy, et al., 1986). Silica is one such element, and is shown by the observation that silica concentration in storm runoff does not vary much with discharge (Kennedy, et al., 1986). Potassium shows a similar tendency for relatively little dilution from baseflow in storm runoff. The apparent reason for the rapid dissolution (or desorption) of soil materials presumably is the existence of a large ratio of soil-surface area to soil-water volume as rain penetrates the soil (Kennedy, et al., 1986).

Silica

Dissolved silica has been used in hydrograph separation studies (Hooper and Shoemaker, 1986, and Scanlon, et al., 2001). It has found favour among researchers because of its absence from precipitation. However, new water has been observed to dissolve silica during even brief contact with the soil (Kennedy, 1971). This characteristic of silica has the ability to introduce error into the hydrograph separation, with an overestimate of the old water component. Dissolved silica is also a biologically active agent used by diatoms (Hooper and Shoemaker, 1986). Uptake of dissolved silica in this manner would lead to an overestimate of the proportion of new water in streamflow. Care should thus be taken in using dissolved silica as a tracer. The conservative nature of dissolved silica is dependent on the soil properties of the watershed and the biological activity in the stream in question.

A common source of silica in rivers is by the leaching of suspended sediment during river transport. Experimental leaching of suspended sediment samples (Kennedy, 1971) concluded that less than 10% of the dissolved silica in the Mattole River resulted from the leaching of river sediments during river transport.

Acid Neutralising Capacity

It has been proposed by Johnson et al., (1981) (as referred to by Hooper and Shoemaker, 1986) that acid rain is neutralised in a two-step process. Fist the incident hydrogen ion acidity is quickly exchanged for aluminium acidity, followed by a slower neutralisation by basic cations (sodium, potassium, calcium, and magnesium). According to this theory, the chemistry of the water is determined primarily by its residence time in the soil. This means that water of short residence time will be more acidic and have a higher aluminium concentration. Because acidic inputs (either storms or snowmelt) to a watershed are event phenomena, we could translate this residence time hypothesis into a hydrograph separation problem, where new water corresponds to water of short residence time and old water corresponds to water of long residence time (Hooper and Shoemaker, 1986).

Electrical Conductivity and Chloride

Chloride is a relatively conservative element that usually occurs in low concentrations in precipitation, and in much higher concentrations in groundwater. Observation of stable chloride concentrations in streams through a storm event have been ascribed to the flushing out of salts accumulated at the land surface during the preceding dry period.

Kennedy et al. (1986) found that such flushing off of salts could not be the reason for consistent chloride concentrations in stream water following a second rain pulse. Kennedy et al. (1986) further notes that relatively stable stream chloride levels, despite intense rainfall, requires a large reservoir of chloride in the soil and sufficiently rapid movement of rainfall into the soil and back out again to contribute substantially to storm runoff.

A likely source of Cl under such conditions is the continued displacement of pre-storm soil water (Kennedy et al., 1986). Another possible source is the Cl held due to the anion exchange capacity of soil clays. Cl sorption on soil increases with decreasing pH, so that acid soils can be expected to adsorp Cl. Even if sufficient Cl were available on exchange sites, it must be displaced in order to be removed in subsurface stormflow. Such displacement could be done in part by divalent SO_4, derived from atmospheric deposition or released during weathering, as a result of enhanced divalent-monovalent competition upon dilution of soil water by rain.

Other chemical tracers

Rice and Hornberger (1998) compared three-component hydrograph separations at peak flow using five different components paired into seven sets (δD and $\delta^{18}O$, δD and Cl^-, δD and sodium (Na^+), δD and silica (SiO_2), Cl^- and SiO_2, Cl^- and Na^+, and Na^+ and SiO_2). Data for 10 storms were collected over a 2-year period in one small, forested catchment in Maryland, USA.

Some of the results obtained from the three component separations were unrealistic and could not be taken to represent actual conditions. Large uncertainties were found in the hydrograph separation solutions. This is ascribed to the violation of assumptions used in deriving the separation equations, and as a result of improper identification of the chemical compositions of end-members. The results of three-component separations using commonly used tracers were widely variable. The study did however observe consistent patterns in the amount of subsurface water contributing to peak flow (45-100%). This was independent of the separation or combination of tracers used.

Through plotting of the temporal change in parameters on mixing diagrams Rice and Hornberger (1998) developed a conceptual model to describe those components that contribute to streamflow. The following conceptual model is presented to explain the pattern observed in the mixing diagrams (Rice and Hornberger, 1998): (1) At the beginning of the storm streamflow is provided by groundwater; (2) as precipitation continues, direct interception of throughfall on the stream channel begins to change the stream water composition; (3) as the storm continues more water infiltrates the ground surface and percolates downward through the soil column and soil water begins to contribute to storm flow; (4) as precipitation peters-off, throughfall and soil water contributions cease and stream flow is again dominated by groundwater.

2.6. Residence Time Determination

Isotopes can be used for determining the ages and residence time of waters, gases, solutes and solid materials in catchments. Two main types of environmental isotopes can be used for age determination: (a) those that mark the occurrence of a particular event, and (b) those that are present world-wide as a result of processes continuing over extended time periods (Kendall, et al., 1992). Examples of the first type of marker include isotopes that were produced and released into the atmosphere in high concentrations during nuclear testing (e.g. ^{3}H, ^{14}C and

^{36}Cl) or accidents such as Chernobyl (e.g. ^{137}Cs). Several isotopes are continuously produced in the atmosphere and have such short half-lives that they label water derived from a particular storm or season (e.g. ^{35}S and ^{7}Be).

Tritium

Tritium has its origin in the upper atmosphere and aboveground thermonuclear testing. The short half-life of tritium, at 12.43 years, makes it a good tracer of modern waters. The presence of measurable tritium levels in groundwater provides evidence for active recharge. Unfortunately the tritium peak experienced in the southern hemisphere was less pronounced than in the northern hemisphere. This tritium peak has decayed to such a degree that the use of tritium is complicated, making it difficult to define an actual water age. Tritium offers the benefit that it is part of the water molecule, and thus represents a method of dating the age of the actual water.

The use of tritium with helium allows for the accurate determination of water age. 3He is a daughter product of 3H decay. This means that in confined systems where dispersion is limited, the 3H/3He ratio is a function of the age of the water.

Chlorine-36

The attractiveness of chlorine in hydrologic studies is that it is highly soluble, exists in nature as a conservative non-sorbing anion, does not participate in redox reactions, and has some quickly identifiable sources (e.g. seawater). Chlorine-36 has been used to date old groundwater in confined aquifers.

The atmospheric concentrations of Chlorine-36 have been elevated by thermonuclear testing. Unlike tritium however, Chlorine-36 has a long half-life (~300,000 years), which precludes its use in dating modern waters. Measurements of ^{36}Cl concentrations in groundwater exceeding about 10^7 atoms.L^{-1} (depending on rainfall and infiltration rates) is a good indication that there is a component of thermonuclear ^{36}Cl and hence, modern recharge (Clark and Fritz, 2001). Because ^{36}Cl is a solute, its use with ^{3}H is recommended in recharge studies. Chlorine-36 has been used to discriminate groundwater bodies and assess degrees of mixing, to determine groundwater flow paths, to place constraints on groundwater age, to identify very young-bomb-pulse groundwater, to determine instances of vertical recharge along a flow path, to identify sources of chlorinity and salinity, to identify sources of salt deposits, to estimate infiltration amounts and depths in arid regions, to make quantitative estimates of evaporation and evapotranspiration, and to investigate paleohydrologic conditions (Nimz, 1998).

Chlorofluorocarbons (CFCs), Argon-39 and Krypton

The stable nature of CFCs makes it a good tracer of water movement. The fact that it occurs as a gas at atmospheric pressure however, makes sampling complicated. CFCs in the atmosphere dissolves in water. The variations in CFC input to the atmosphere means the time of exposure of the water to air can be established. The period of CFC input to the atmosphere is relatively recent, and restricts this method to water that are only a few decades old.

The use of argon and krypton is restricted to a limited number of laboratories, because of the complications in sampling, analysis and interpretation. These elements occur as gasses in nature and require huge volumes of water vacuum extracted in the field to obtain a sample.

Carbon-14

Age dating old groundwater begins with a determination that they are tritium-free, and so have no modern component. The only absolute technique for the dating of sub-modern or older water involves the decay of long-lived radio-nuclides. By far the most routinely applied is ^{14}C (half-life 5730 years), which is transported as dissolved inorganic carbon (DIC) or dissolved organic carbon (DOC).

Measurements of ^{14}C are reported as percent modern carbon (pmc), determined as the ratio of the sample activity to that of the international standard expressed as a percentage. The main problem in applying this method is that some reactive minerals contain carbon, and carbon transfers in and out of the groundwater. These interactions can reduce the ^{14}C activity in the water and thus need to be fully accounted for in age estimation. Like ^{3}H, atmospheric weapons testing have affected its concentration. This may in cases prove useful in identifying modern groundwater recharge.

The ^{14}C content of groundwater may be altered by a number of processes, and these need to be accounted for before ^{14}C can be used in age dating. The ^{14}C method is at best a semi-quantitative tool. Confident predictions can be made only when the processes affecting the carbon chemistry are absolutely defined.

It is possible to precisely measure small amounts of ^{14}C in DOC. Like DIC, ^{14}C-active DOC is derived from the groundwater in the soil zone. Unlike DIC, however, it is unaffected by dilution during the host of carbonate reactions experienced by groundwater, and so provides an independent method to date groundwater. Dating groundwater with DOC is not without methodological difficulties. Its concentration in groundwater is typically less than 1 mg-C/L, which makes sampling difficult. A sample of at least 100 L is then required.

Carbon-13 is an excellent tracer of carbonate evolution in groundwater. The large difference in $\delta^{13}C$ between the soil-derived DIC and carbonate minerals in the aquifer can provide a reliable measure of ^{14}C dilution by carbonate dissolution. The $\delta^{13}C$ mixing model allows for the incorporation of ^{14}C-active DIC during carbonate dissolution under open system conditions, and subsequent ^{14}C dilution under closed system conditions.

2.7. Flow path and Travel Time

Typically catchments are characterised by a distribution of travel times, reflecting the diverse flow paths that rainfall takes to streams. Catchments are spatially complex and subsurface flow invisible, so one can only infer the movement and mixing of waters from the isotopic and chemical tracers that they carry. Kircher, et al. (2000) used chloride as a chemical tracer to quantify water travel times. By comparing the chloride signatures of rainfall and runoff through time, they were able to measure how long their study catchments retained a chemical memory of the rain that had fallen. Each day's rainfall influences stream chemistry in future days by an amount that is determined by the travel time distribution. Equivalently, the present concentration in the stream reflects the rainfall concentrations throughout the past, weighted by their fractional contribution to the present runoff. The dampening of tracer fluctuations from rainfall to streamflow can be used to infer a catchment's travel time distribution.

Kircher, et al. (2000) uses the following mathematical equation to determine travel time:

$$C_s(t) = \int^{\infty}_{0} h(\tau)c_R(t-\tau)d\tau \qquad (1)$$

Mathematically this means that the stream concentration $Cs(t)$ at any time is the convolution of the travel time distribution $h(\tau)$ and the rainfall concentration $c_R(t-\tau)$ throughout the past, where τ is the lag time between rainfall and runoff:

2.8. Discussion

The application of environmental isotopes in streamflow generation studies has allowed hydrologists to develop greater insight into the processes at work in catchments during rain or snow-melt events. As a result the conventional thinking on the processes at work in catchments have been questioned and new theories to explain these processes have been developed (e.g., Freeze, 1972, Mosley, 1979, McDonnell, 1990, and McDonnell and Buttle, 1996). From this it follows that research into catchment hydrology processes requires the application of a combination of isotope - geochemical techniques and hydrometric observations.

The headwater catchments found in the mountains of the Western Cape are different from the catchments in other parts of the world where research on streamflow generation have been conducted. These mountains are characterised by the unique combination of almost pure quartzitic sandstones, many hundreds of metres thick, which have been subjected to episodes of folding and fracturing. It is therefore assumed that the streamflow generation processes at work in these catchments differ from that observed in other parts of the world.

The methods developed in research studies throughout the world could find useful application in the TMG headwater catchments. Through the use of stable isotopes the relative contributions of "new" and "old" water should first be established. From this analysis and with the added use of other tracers, e.g. Silica or Dissolved Organic Carbon, greater insight could be developed on the flow path of water to the streams.

The dating of water could be a valuable tool in such flow path determinations. It appears as if the use of tritium may find limited application in South Africa. Though the use of CFCs has potential, its use is complicated by the difficulty of obtaining an unpolluted sample. Chlorine-36 is another method with potential, and could be used to discriminate between groundwater bodies and could put a constraint on the groundwater age. The general convention is to use more than one method in groundwater age determination. This together with the flow characterisation developed through the use of the environmental isotopes would provide valuable insight towards the development of a conceptual model on the processes of recharge and streamflow generation in TMG catchments.

3. Study site description

3.1. Location

The Zachariashoek research catchments are located about 35 kilometres North-east of Stellenbosch and 15 kilometres east-south-east of Paarl. The site forms part of the La Motte state forest under the control of Safcol, and lies between the Klein Drakenstein and Wemmershoek Mountains. Approximate location of the study area is at latitude 33° 48'South and longitude 19° 02' East. The area has been the focus of intense hydrological research since 1965.

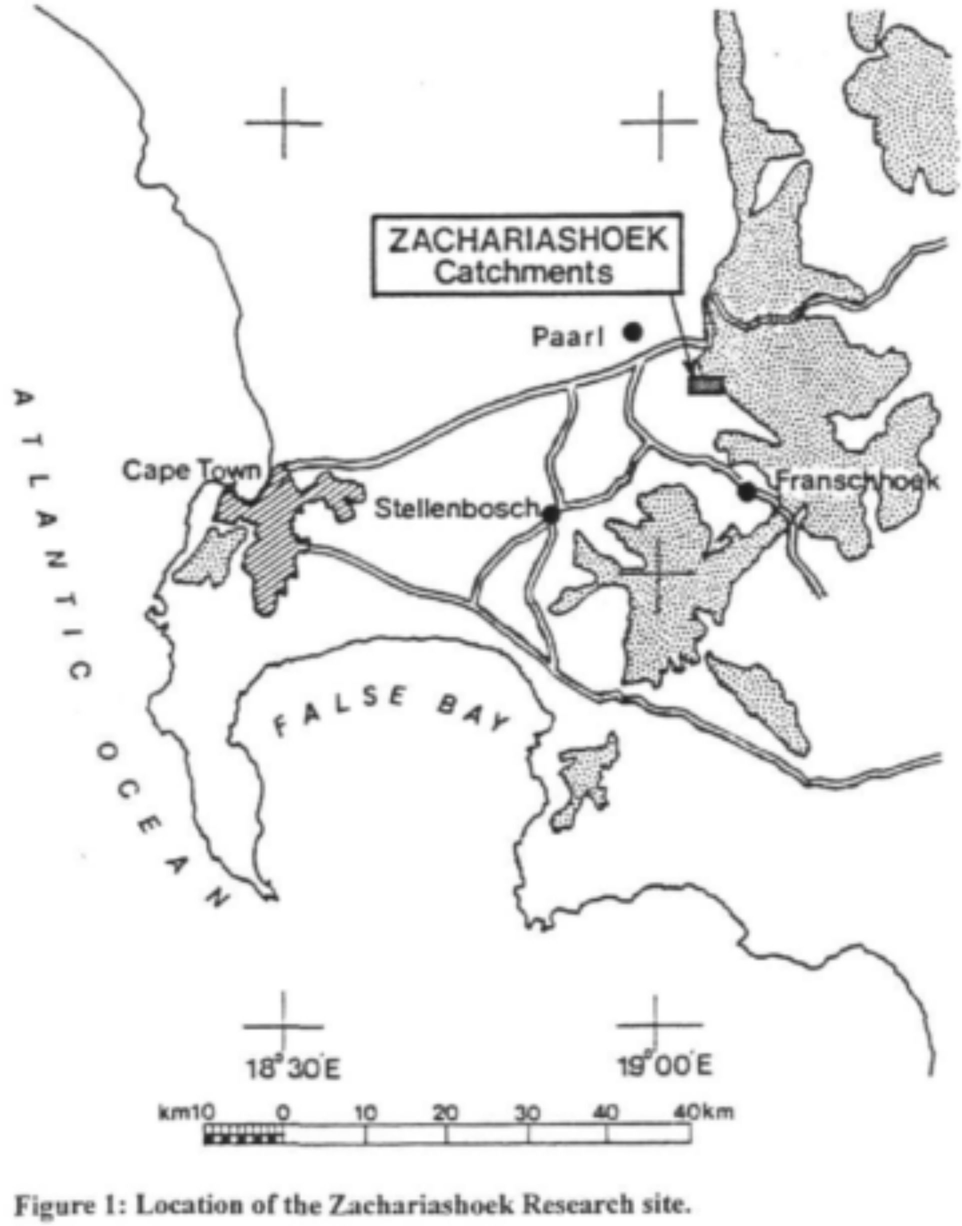

Figure 1: Location of the Zachariashoek Research site.

Three sub-catchments are found in the study area, Kasteelkloof (324,5 ha), Zachariashoek (287 ha) and Bakkerskloof (356,4 ha). The catchments are situated on a broken plateau which rises abruptly from the valley of the Berg River. Mean elevation at the research site is about 675 m amsl. The Kasteelkloof catchments border to the North-east on the catchment of the Wemmershoek dam, one of the main sources of water supply for the city of Cape Town. The catchments form the source of the Wemmers River, which joins the Berg River 4 kilometres south of the research catchments.

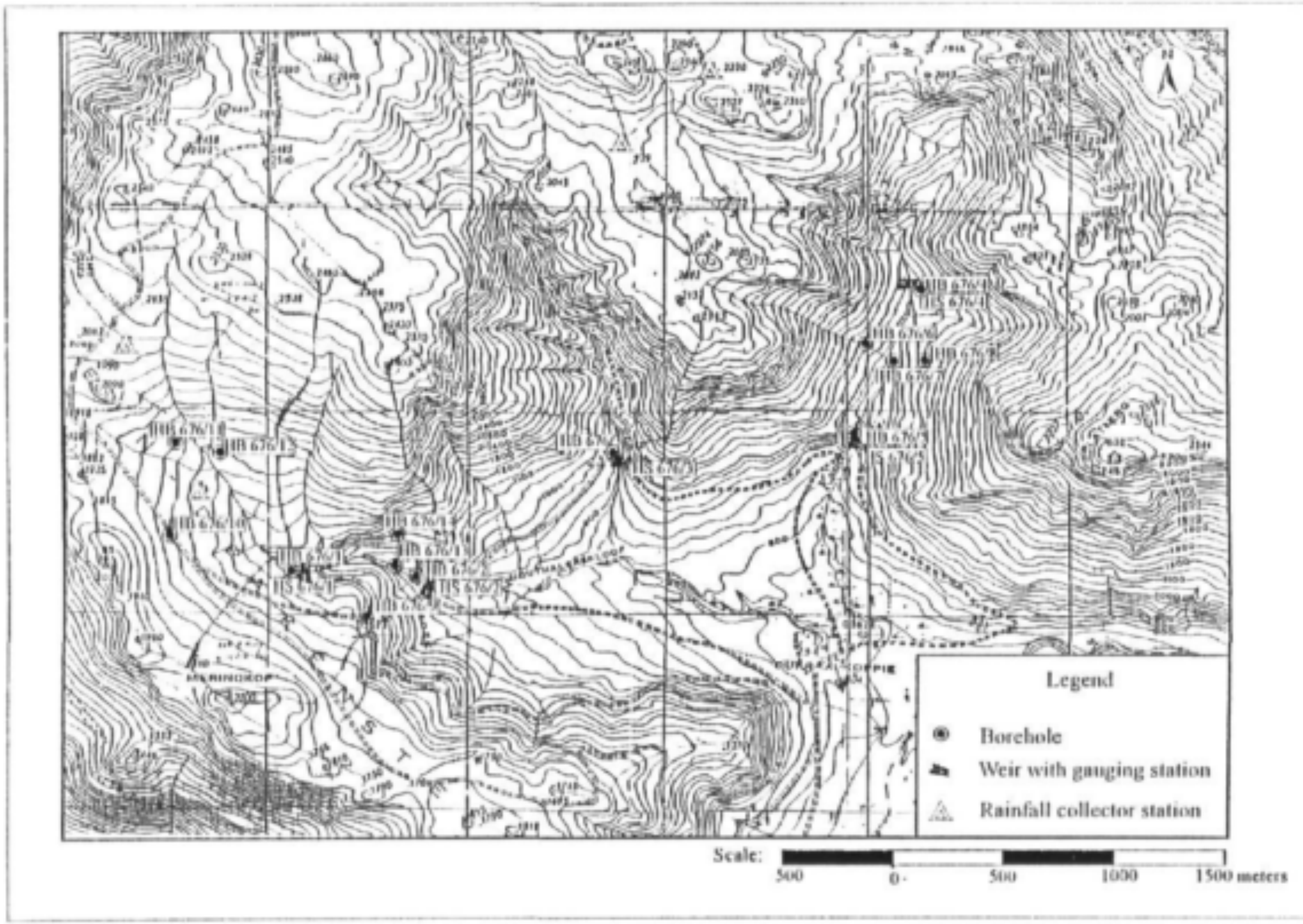

Figure 3: Zachariashoek study site with the location of weirs, boreholes and rainfall collector sites.

3.2. Climate

Average daily temperature at the Zachariashoek site is 14.8°C, with average annual precipitation 1293 mm (at average elevation of 717 m amsl). Most rain falls during the winter months, with the months between April and September receiving in excess of 100mm/month.

The steep topography results in precipitation variation over the study site. Historical rainfall data as published by Van Wilgen and Kruger (1981) are presented in Table 1. A trend of increased precipitation with increased altitude is observed. A linear regression of mean annual rainfall (y) in mm against altitude (x) in meters is presented by Van Wilgen and Kruger (1981): $y = 819.42 + 0.83x$ ($r2 - 0.46$, $P<0.05$)

Table 1: Mean annual precipitation at the Zachariashoek research site (1968 - 1977)

Rain-gauge	Years of observation (hydrological years)[a]	Altitude (m)	Mean annual precipitation (mm)
Zachariashoek 1	1968/69 – 1983/84	625	1012
Zachariashoek 2	1968/69 – 1983/84	335	981
Zachariashoek 3	1978/79 – 1983/84	785	1376
Zachariashoek 4	1978/79 – 1983-84	338	1175
Zachariashoek 5	1968/69 – 1983/84	677	1612
Zachariashoek 6	1968/69 – 1983/84	305	1265
Zachariashoek 7	1976/77 – 1983/84	640	1643
Zachariashoek 8	1976/77 – 1983/84	488	1206
Zachariashoek 9	1976/77 – 1983/84	717	1293

In analysing wind data from the period 1976 to 1979 by Van Wilgen and Kruger (1981) found that the daily wind-run at the Zachariashoek study site was much higher than at a lower elevation weather station. At the Zachariashoek site the maximum wind-run is experienced in winter, while at the lower elevation Bien Donne weather station the maximum wind-run is in summer. For the winter half year (April – September) wind is mainly from the north or north-west and in the summer half-year it is predominantly from the south-east, but with a fair percentage from the north-west and west.

3.3. Topography

The upper parts of the three catchments consist of an undulating plateau with shallow basins. Some of the cachment divides are ill-defined, while other catchment boundaries consist of abrupt escarpments or steep talus slopes.

3.4. Geology

The geology of the research area is dominated by rocks of the Table Mountain Group (TMG) succession. Three formations are found in the study area. These are the Nardouw formation, the Cedarberg shale formation and the Peninsula formation. Wilson (1966) found minor faulting present which partially controls the positions of the feeder streams originating in seepages on the upper slopes. The geology as defined by Wilson (1966) is shown in Figure 4.

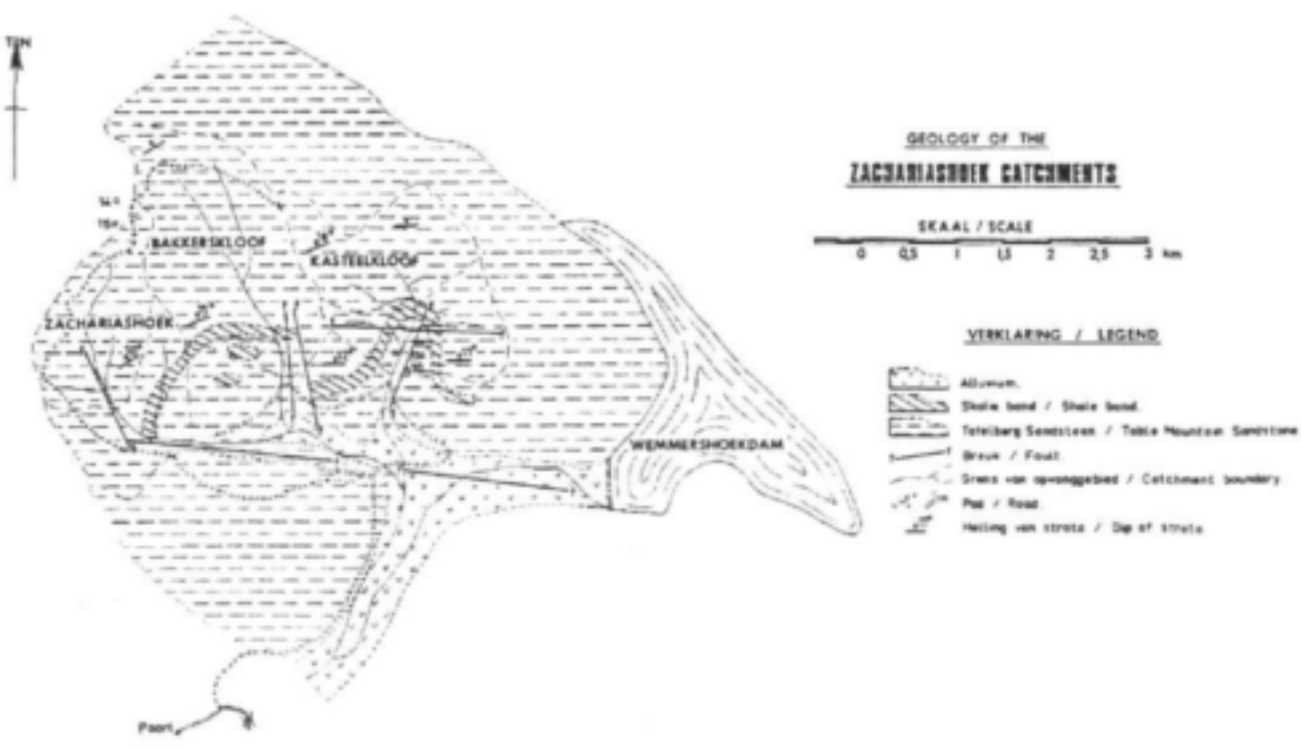

Figure 2: Detailed geology of the Zachariashoek study site. (Source: Wilson, 1966)

The Table Mountain Group is one of three successions that form the Cape Supergroup that occur along the South African west and south coast. The TMG consists of 95% quartz arenite of medium to coarse grain-size, and variable amounts of feldspar and clay (de Beer, 2001). This, together with the thick nature of the succession (more than 2000 meters in places) and its highly fractured nature makes the TMG aquifer one of the major fractured aquifers of South

Africa. Uncertainty however exists on the hydraulic properties of the aquifer, with hydraulic conductivity estimated between 1.99 and 1.99 x 10^{-3} m/d. and Storativity of between 1 x 10^{-4} and 5 x 10^{-2} (Rosewarne, 2001).

3.5. Soils

Soils are derived mainly from quartzites of the Table Mountain Group, except on and below the Cedarberg shale band. The soils are oligotrophic due to their coarse sandy texture and the relatively high rainfall. The base status is low, with the sum of exchangeable cations less than 5 me/100g clay. The soils are acid, which is typical of montane fynbos sites, and pH ranges between 4 and 6 when measured in H_2O paste, and 3 to 5 when measured in KCl. The clay content is less than 8% over most of the area, indicating a low water retention capacity.

3.6. Vegetation

Vegetation is largely of the mountain fynbos type. When research at the site started, much of the area was heavily invested with *Hakea sericea* and self-sown P*inus pinaster*. A systematic eradication programme has been implemented at the research site through uprooting, slashing and burning of single plants or thickets of it (Van der Zel, 1974).

A review on the impact of burning on vegetation at the study site (Van Wilgen and Kruger, 1981) showed that the relative abundance and distribution of vegetation communities seems to be governed largely by moisture regime in terms of water availability and drainage potential. Other governing factors include altitude, aspect and geological formation. The low stunted nature of vegetation in exposed areas is ascribed to the considerably higher mean wind speeds in the upper catchment. Fire is another factor that influences the distribution of vegetation communities. Van Wilgen and Kruger (1981) note that total biomass is lower than at other mountain fynbos areas of similar age. This is ascribed to the frequent burning of the area in the past to promote grazing, and a subsequent encroachment of the invasive exotic shrub *Hakea sericea.*

3.7. Past Studies

Hydrological research has been conducted at the Zachariashoek research site since 1965 (Wilson, 1966, Van der Zel., 1974, Van Wilgen and Kruger, 1981, Van Wyk, 1982, and

Lindley, et al., 1988). This formed part of a larger research study conducted at a number of research sites, designed to determine the influence on water yield of prescribed burning in fynbos. It was hoped that the results of these studies would provide benchmark information on streamflow response to management of veld, and would so contribute to the development of a hydrological decision model of natural veld catchments.

3.8. Monitoring Infrastructure

Visits were made to the Zachariashoek research site in March and May to assess the state of the monitoring infrastructure.

Weirs and Gauging stations

A total of five weirs and gauging stations were built in the three Zachariashoek research catchments. Most of the problems noted is largely the result of neglect. Since monitoring at these sites were ended in 1996, no maintenance had taken place. As a result it was found that silt had built-up on the upstream side of all the weirs. However, in the case of weirs HS676/1 and HS676/5 the monitoring infrastructure had been partly demolished. This included the removal of the V-crests as well as the recorder house. A summary of the state of the Zachariashoek weirs is given in the Table 2.

Table 2: State of weirs and gauging stations (2001).

Weir number	Sub-catchment	Repairs required
HS 676/1	Zachariashoek Bo	- Removal of silt, replacement of v-crest, new v-crest bolts, a new recorder house and repair of the stilling pool, automatic data recorder.
HS 676/2	Zachariashoek Onder	- Removal of silt, replacement of v-crest, automatic data recorder
HS 676/3	Bakkerskloof	- Removal of silt, replacement of v-crest, automatic data recorder
HS 676/4	Kasteelkloof Onder	- Removal of silt, replacement of v-crest, automatic data recorder
HS 676/5	Kasteelkloof Bo	- Removal of silt, replacement of v-crest, new v-crest bolts, a new recorder house and repair of the stilling pool, automatic data recorder.

During a site visit it was found that the monitoring infrastructure that exists in the three catchments, while essentially sound, is in need of repair. The following list of repair work was made:

1. The 5 Weirs and gauging stations require:
   - the bedload and sediment that has deposited on the upstream side of the weirs to be dug out to re-create capacity in the stilling ponds, and
   - the sharp crested V-notches in the weir walls to be replaced (the construction of these allow replacement notches to be bolted into place).
   - the weir walls should be checked for leakage, and sealed where necessary

2. The instrument huts are in need of repair:
   - They could do with a coat of paint on the inside,
   - The stilling chambers and the pipes that lead to and from them should be cleared out.
   - The cover plates of the stilling chamber pipes are probably in need of replacement (this can only be checked once the stilling ponds have been cleaned).

3. Maintenance and repair of the 14 boreholes found in the study area.
   - Our preliminary survey has shown that at least 4 of the boreholes had collapsed or were filled with debris.
   - The casing on all the boreholes are rusted and possibly close to collapse.

4. The access road system needs some minor repair work to allow us to gain access to the whole monitoring system without causing further damage to the nature reserve and erosion in particular.

Boreholes

Most of the boreholes have either collapsed or been filled with silt that washed into the hole subsequent to the removal of the five automatic water level recorders (HB 676/1 – 5) Some of the boreholes has been overgrown with vegetation and could not be located. Their condition remains unknown. A summary of the state of the boreholes at the Zachariashoek research site is given in Table 3.

Table 3: State of the Zachariashoek research site boreholes (2001).

Borehole number	Sub-catchment	Borehole status
HB 676/1	Zachariashoek	silted-up
HB 676/2	Zachariashoek	silted-up
HB 676/3	Bakkerskloof	silted-up
HB 676/4	Kasteelkloof	silted-up
HB 676/5	Kasteelkloof	silted-up
HB 676/6	Kasteelkloof	temporarily lost
HB 676/7	Kasteelkloof	temporarily lost
HB 676/8	Kasteelkloof	temporarily lost
HB 676/9	Zachariashoek	Collapsed
HB 676/10	Zachariashoek	open to 11.21 metres
HB 676/11	Zachariashoek	open to 17 metres
HB 676/12	Zachariashoek	temporarily lost
HB 676/13	Zachariashoek	temporarily lost
HB 676/14	Zachariashoek	temporarily lost

Weather stations

All weather station and rain collector equipment has been removed from the Zachariashoek research area. The locations of the weather stations are known, which provides valuable insight to the characterisation of the local climate.

4. Historical Data Analysis

4.1. Introduction

An analysis of some of the historical data available for the Zachariashoek research site was done in order to further inform the development of a research strategy for detailed field research. It was hoped that the analysis would inform the research team on the differences and/or similarities between the three Zachariashoek catchments. If the three catchments were found to be very similar in their hydrological characteristics, the field research could focus on only one of the catchments and assume that the results would be applicable on the others as well. However, should major differences exist, the field research would have to acknowledge these, either through focus on more than one of the catchments, or by accepting that the results could not be applied to all TMG headwater catchments without consideration of the implications of their differences.

4.2. Methodology

The Zachariashoek research site has historical data that stretches back to 1965. A catalogue of the data that is available for the Zachariashoek research site is presented in Appendix B. For the purposes of comparison, a period was selected for which complete data sets exist for both rainfall and streamflow (1968 – 1985). For both rainfall and streamflow the annual mean and median values were calculated.

The aerial precipitation was estimated through averaging; using two different methods:

1. The altitudinally weighted Thiessen polygon method, and the
2. Isohyetal interpolation method.

The Thiessen polygon method is based on the hypothesis that, for every point in an area, the best estimate of rainfall is the measurement physically closest to that point. The Thiessen polygons are defined by drawing perpendicular bisectors to straight lines connecting each two rain-gauges. This yields, when the watershed boundary is included, a set of closed areas known as Thiessen polygons. When using altitudinally weighted Thiessen polygons, the mid-elevation between rain-gauges are used to separate them. In the Isohyetal method rainfall amounts from a set of gauges are plotted on a map of the region. Lines connecting all points of equal precipitation are then connected to create an isohyetal map.

The streamflow data recorded by Belfort recorders at each of the five weirs were digitised and entered into a locally developed data management package called ACSYS. Once entered, the software can be used to generate information on the monthly proportions of runoff, and the quickflow and low flow components of runoff for each of the five sub-catchments. A statistical analysis package, SAS (Statistical Analysis Software) was used for data analysis and to produce the outputs presented in Table 4. The data and analysis generated were compared with similarly long-term data from the Jonkershoek research catchments.

4.3. Results and Conclusions

The following table summarises the results of the Zachariashoek rainfall and streamflow data analysis.

Table 4: The hydrological characteristics of the gauged catchments at Zachariashoek.

Hydrological Variable	Zachariashoek Upper	Zachariashoek Lower	Bakkers-kloof	Kasteelkloof Upper	Kasteelkloof Lower
Weighted Mean & median Annual Rainfall – {altitudinally weighted Thiesen}.(1969 - 1985)	1032.1 1008.7	1035.4 1014.1	1393.1 1392.2	1472.1 1462.3	1411.9 1386.2
Weighted Mean rainfall (mm)- {Isohyetal interpolation}	1125.7	1082.6	1371.4	1617.2	1557.4
Mean (median) Annual Runoff (mm) same interval as rainfall (1969 - 1985)	342.0 244.8	389.9 325.5	458.3 459.6	855.4- 747.9	766.25 680.
Inferred evaporation (P - Q) from means & medians	670 765	646 688	913 933	617 714	791 706
Proportion of runoff April – September (%)	84	82	90	85	83
Mean & median annual Quickflow • (mm)	65.7 31.2	77.6 49.2	195.7 188.8	347.7 286.7	271.7 205.4
Annual response (MAR/MAP) %	28	30	37	67	50
Quickflow • response (Qq/Qtot) %	19	19	43	41	35
Annual Low flow ☼ volume (mm) Mean & Median	5.695 5.663	12.148 12.177	4.92 4.755	14.726 14.146	20.882 21.00
Low flow ☼ as proportion of Total (Qq/Qtot %), from means & medians	1.67 2.31	3.12 3.74	1.07 1.03	1.72 1.89	2.73 3.07

● **Quickflow** is as defined by Hewlett and Hibbert (1967), and is in effect the storm hydrograph minus the estimated baseflow component.

☼ **Low flow** is that flow below the seventy-fifth percentile exceedance level, determined on the daily flows dataset.

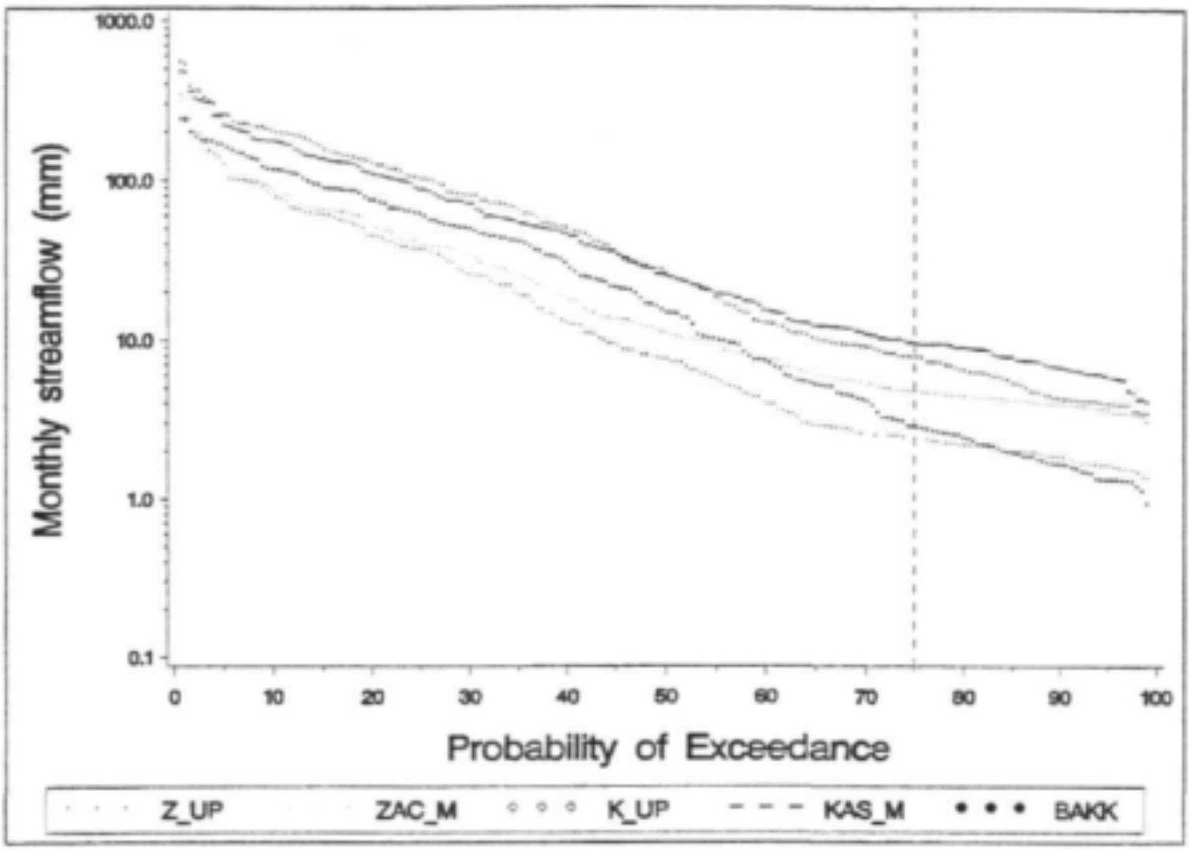

Figure 3: Flow duration curves for the five gauged catchments at Zachariashoek. The vertical line at probability of 75% indicates the low flow cutoff.

There is a remarkable difference between the runoff responses of the five gauged-catchments considering the apparent similarities in catchment physiography. As expected there is a higher rainfall catch at higher altitudes, but more important is the sharp rainfall gradient from West to East, as one approaches the higher mountains of the Wemmershoek range. Table 4 shows the influence of this rainfall gradient on the estimated weighted mean rainfall for each catchment, which ranges from just over a 1000 mm/yr to around 1500 mm/yr. The rainfall gradient is also reflected in the higher runoff (MAR) and higher proportional yield in Bakkerskloof and Kasteelkloof compared to the Zachariashoek catchment (Table 4).

The wetter, steeper and rockier Bakkerskloof and Kasteelkloof have notably higher quickflow (the upper parts of the storm hydrograph) than is recorded in Zachariashoek. This indicates a lower (soil water) storage capacity in these catchments. Overall though, the quickflow volumes are high in absolute terms (means between 65 and 350 mm per annum) and as a proportion of the annual runoff (between 19 and 43% of total).

Midgley and Scott (1994) conducted research on streamflow processes in the Jonkerhoek research catchments near Stellenbosch. Similarities in vegetation, topography and climate makes comparison between the Jonkershoek and Zachariashoek catchments relevant to the understanding of the Zacharishoek flow processes. Comparisons show that the Jonkershoek quickflow volumes are generally smaller (less than 10% in some) than those reported here for the Zachariashoek research site. The low storage in the Zachariashoek catchments is confirmed in the meagre summer low flows in the catchments. Low flows, defined as flows below the 75th percentile exceedance level make up considerably less than 5% of the annual flow volume. This low figure is perhaps accentuated by the high annual flows, but is lower than recorded in the equally wet Jonkershoek catchments, also in the TMG, where mean runoff in the single driest month would generally be about the same as recorded in three months at Zachariashoek.

The flow duration curves (FDCs; Figure 3) are generally similar in shape, but there are important differences. Obviously the higher yield from the wetter Kasteelkloof places the curves for this catchment above the others. The important difference between the curves for the two Kasteelkloof gauges is that the low flow component is better sustained at the lower station. The low flow volume is also greater per unit area at the lower station. These points indicate that there is a greater groundwater discharge contributing to the surface flow at the lower gauge.

The Bakkerskloof FDC is very similar to that of the upper Kasteelkloof station, but the sustenance of low flows is even weaker, and low flows are lowest in this catchment and particularly in relation to the total yield from Bakkerskloof.

The Zachariashoek catchment is drier and this is apparent in the FDCs by the lower yields, particularly during the wet season. However, the catchment is less responsive and appears to store water better than the other catchments as indicated by the particularly well-sustained low flows at the main gauge (Zach. Lower). One other aspect is apparent from the shape of the FDCs. In the nested catchments (Zachariashoek and Kasteelkloof) the lower stations have significantly greater and better sustained low flows. This presumably indicates the incremental contribution of subsurface flow paths further down the catchments.

The results suggest that the Zachariashoek catchment is substantively different from the other two catchments. It would therefore be advantageous to study both this and another catchment as part of an effort to understand TMG catchments and groundwater flow paths. As both Zachariashoek and Kasteelkloof have two gauging stations within them, and more groundwater monitoring points within them, it would make sense to suggest these two catchments. The study of both is recommended since they exhibit significant differences in responses from similar excitations.

4.4. Discussion

Judging by the high quickflow responses of the catchments, and the small low flow contribution to the total flow it is clear that these headwater catchments have relatively little storage capacity that contributes to sustained flow. Such storage capacity may be of a saturated or unsaturated form but it's essential quality is that it contributes to delayed flow in the surface water yield. It is also clear from the results in the nested catchments (Zachariashoek and Kasteelkloof) that there is more low flow, and better sustained low flow at the lower monitoring stations than at those in the upper portions of these catchments.

Without making too many assumptions regarding the sources of water, it is clear from the very low flow volumes in the driest months (low flow in Table 4), and from the low summer yields relative to rainfall (Figure 3), that there is a limited supply of streamflow from "delayed flow" sources – what might be assumed to be true groundwater discharge. It might be that the catchments are all too high in the mountains to show a large dry season baseflow from groundwater.

This is also in contrast to the Jonkershoek catchments that clearly have a greater proportion of "delayed flow" (Figure 4). Whether one classifies this delayed flow as groundwater or not, it is highly probable that it has reached the stream *via* saturated pathways, and is certainly subsurface water. In Jonkershoek, the streamflow peak is clearly lagged behind the peak in rainfalls, and baseflows are well sustained through the dry months; the water clearly coming from stored water rather than recent rainfall.

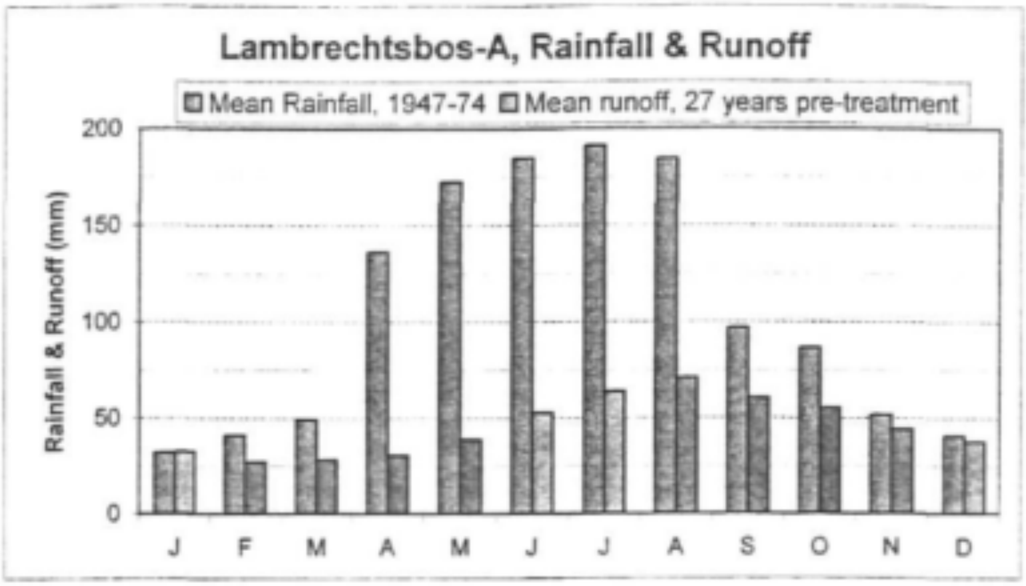

Figure 4: The water balance of the Lambrechtsbos B catchment in Jonkershoek which has a high elevation range and is fairly narrow, indicating relatively little apparent storage capacity.

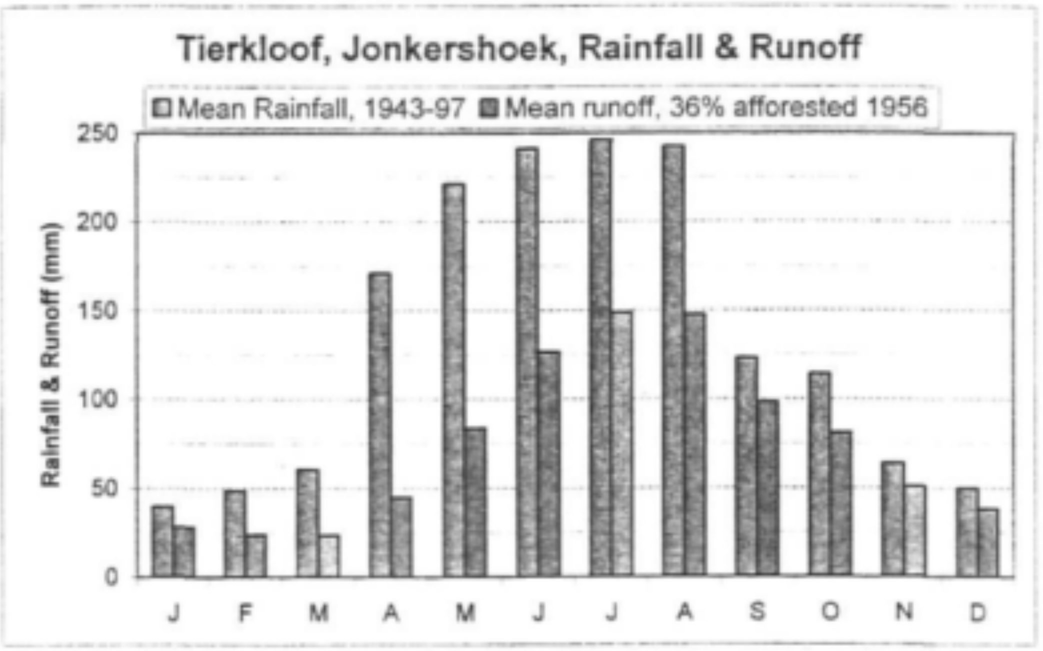

Figure 5: The water balance of the Tierkloof catchment in Jonkershoek, which, like Kasteelkloof, has a high rainfall and even more cliff and shallow rock in the upper elevations.

4.5. Conceptual model of TMG Headwater flow processes

A conceptual model of flow processes in Table Mountain Group headwater catchments like those at the Zachariashoek research site. The following figure (Figure 6) and table (Table 5) provides a summary of present understanding on the flow mechanisms in TMG catchments.

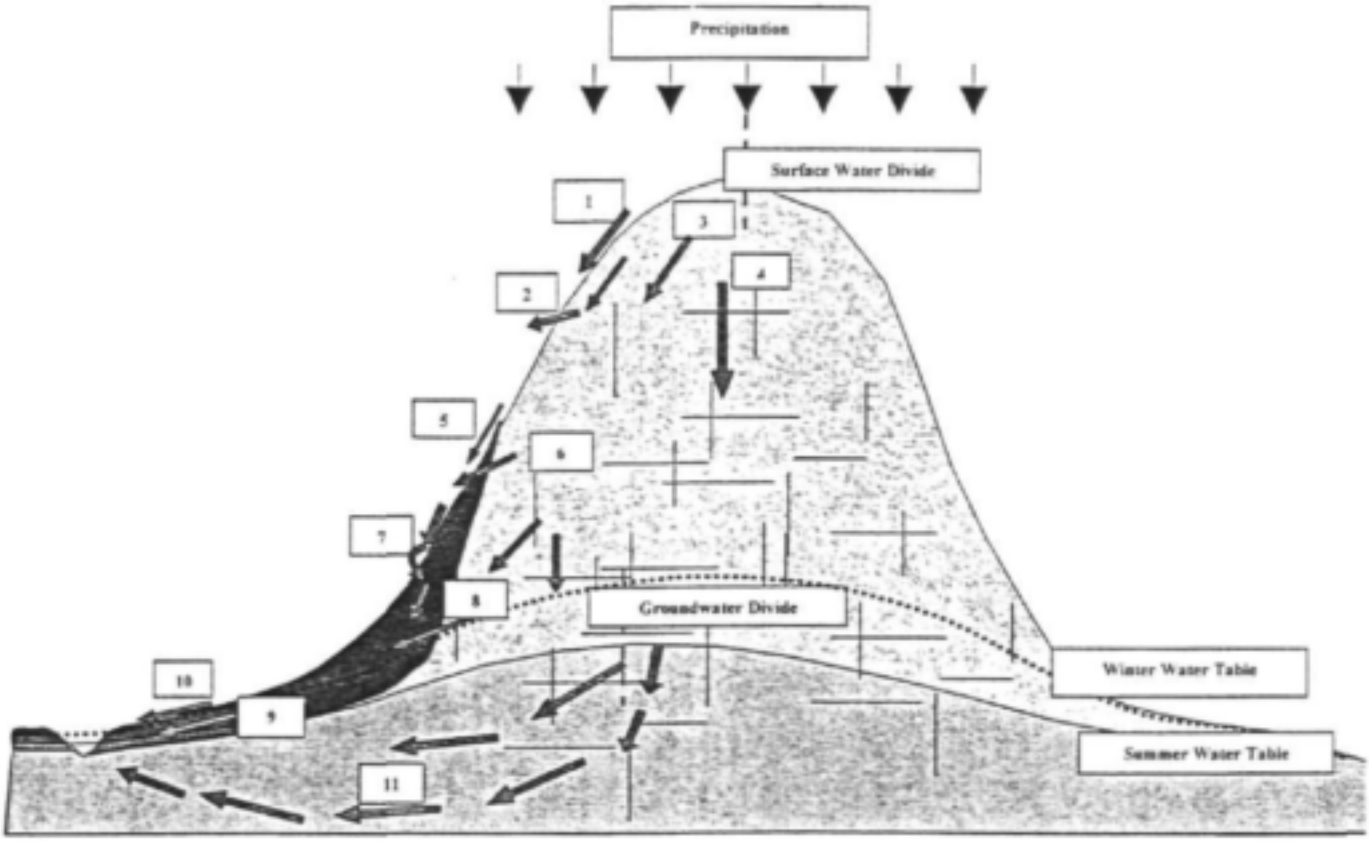

Figure 6: Conceptual model of flow processes in TMG headwater catchments.

Table 5: Description of flow processes in TMG catchments.

No.	Description
1	Surface runoff from rock outcrop on steep slopes.
2	Emergence of spring water and seepage from fractured rock.
3	Lateral induced flow in fractured rock due to hard-rock fracture orientation.
4	Vertical recharge flow in fractured rock due to fracture orientation
5	Local surface runoff from soil profile
6	Preferential flow in soil profile due to: ○ macropore structures ○ groundwater ridging in perched water table
7	Re-infiltration of surface water into soil profile in shallower slopes with a deeper soil profile.
8	Re-emergence of lateral fractured flow component into soil profile.
9	Preferential flow in soil profile
10	Local surface runoff as in 5.
11	Groundwater aquifer lateral flow due to gradient of phreatic surface and flow paths in the groundwater system.

5. Conclusions and Recommendations for Future Work

5.1. Conclusions

International experience has shown that the application of isotope and geochemical techniques can provide valuable insight into the components that make up stormflow. In this way these techniques has the potential to contribute significantly to the understanding of the hydrological processes in humid headwater catchments, when used in conjunction with hydrological flow analysis.

During this study, the Zachariashoek research catchments was identified as suitable for the testing of the applicability of isotope and geochemical techniques with hydrometric methods under South African conditions. At the same time the results obtained could find application in the management of groundwater abstraction from the Table Mountain Group aquifer and the understanding of the possible environmental impacts that may arise from such abstraction.

Analysis of historical flow data from the Zachariashoek research catchments showed that these headwater catchments have relatively little storage capacity that contributes to sustained flow. Comparisons show that the nearby Jonkershoek catchments have a greater proportion of delayed flow.

The flow analysis further showed that the Zachariashoek sub-catchment differs in a number of ways from the other two research sub-catchments. The most complete understanding of the hydrological processes in these catchments can thus be obtained by studying the Zachariashoek sub-catchment and one of the other two sub-catchments. The better monitoring infrastructure in the Kasteelkloof sub-catchment makes it the preferred second catchment for field study.

5.2. Recommendations for Future Work

Detailed field research that looks to identify the mechanisms of streamflow generation and develops a better understand of the flow paths that water follow to streams will make a valuable contribution to the understanding and management of fragile headwater catchments. Research is underway and will study the impact of groundwater abstraction from the TMG aquifer on ecosystems. A better understanding of flow processes in the headwater catchments of the TMG will be required if the results of that study is to be applied to the management of groundwater abstraction from TMG aquifers.

This study highlights the contribution that isotope and geochemical techniques could make to the understanding of flow and streamflow generation processes in South African headwater catchments. The increasing volume of published literature further emphasises the need for hydrological research to utilise a combination of hydrometric and isotope/geochemical techniques in the development of a proper understanding of the flow processes at work in headwater catchments.

One of the outputs of this study is the development of a research programme for detailed fieldwork based on the findings of this study. Table 6 gives an example of the tasks that are envisaged as part of a detailed field research study in the Zachariashoek research catchments.

Table 6: Tasks to be included in a detailed field study on the processes of streamflow generation, with specific reference to streamflow generation research at the Zachariashoek research catchments.

Descriptive analysis of the Zachariashoek Research Catchments

This would include:

- The costing and prioritisation of tasks.
- Catalogue historical data (including details on format and status).
- The use of historical streamflow, rainfall and chemistry data to :

1. Generate and compare flow duration curves for each of the research catchments as part of their characterisation,

2. Determination of the quickflow component in event hydrographs through the Hewlett and Hibbert method to indicate the relative size of stormflows.

3. Water balance analysis for the study site [$P = Q + E + \Delta S$].

4. Generate Master Recession Curves as a means of comparing the catchments, and to characterise the baseflow yield characteristics.

5. Review the borehole water levels to check the functioning of the boreholes.

7. Use the historical data to compare borehole EC levels with stream-water EC values.

8. Use the available EC and Chlorine data to see what is useful, if anything, for understanding the changes in water sources down the length of the stream channel.

Purchase a Digital Terrain Model for the study site, and do a drainage analysis (ln[A/cos2]) for the research area, and compare this to a field mapping of hydromorphic communities.
Install EC probes along stream length to determine the contributions of different flow paths or components to streamflow down the channel.
Do baseline water sampling to characterise water chemistry and to find "labels". Sampling should include: rainfall, seeps, streams and groundwater. The rainfall sampling will require cumulative samplers with taps. Chemical analysis should include chloride, DOC and silica.
Plan for the upgrade of monitoring infrastructure and the installation of new infrastructure. This includes the erection of rainwater collectors, weather stations, new boreholes and the rehabilitation of some of the old ones, and the repair and building of additional gauging stations. The purchase, renovation or construction of automatic stream and rainfall collectors also need to be planned.
Do detailed studies of rainfall events over two rainy seasons. It is proposed that about six large storm events be sampled in each year. Each event will require a detailed and complete characterisation. This will require sequential sampling of rainfall and streamflow
Longer interval, continuous monitoring of rainfall, stream and groundwater chemistry (isotope signals) will be performed by means of bi-weekly sampling; samples are to be analysed for oxygen-18, chloride and other potential labelling variables.
Sampling at longer intervals of the Tritium or CFC content of waters to determine the age and residence time of the water in the catchments.

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Appendix 1:

List of participants to the Isotope Hydrology Workshop held in Stellenbosch on the 21st of May 2001.

Jeff Mc Donnell	Catchment Hydrologist, University of Oregon (Guest speaker and discussion leader)
Irené Saayman	Hydrogeologist, CSIR
John Weaver	Hydrogeologist, CSIR
Dave Scott	Forest Hydrologist, CSIR
Siep Talma	Isotope Chemist, CSIR
Dave Le Maitre	Ecologist/Hydrologist, CSIR
Lisa Cavé	Geochemist, CSIR
Sean Jacobs	Ecophysiologist, CSIR
Christine Colvin	Hydrogeologist, CSIR
Jinhui Zang	Numeric Modeller, CSIR
Jan Bosch	Forest Hydrologist, CSIR
Colin Everson	Catchment Hydrologist, CSIR
Mike Smart	DWAF, Geohydrology, Western Cape Regional Office
Reagan Rose	DWAF, Geohydrology, Western Cape Regional Office
Shafiek Adams	Hydrogeologist, University of the Western Cape
Anthony Fielies	Hydrogeologist, University of the Western Cape
Jeremy Midgeley	Ecologist, University of Cape Town
Roger Parson	Hydrogeologist, Parsons and Associate
Jeff Jolly	Hydrogeologist, Groundwater Consulting Services
Jerry Papini	Hydrogeologist, Groundwater Consulting Services
Chris Hartnady	Hydrogeologist, Umvoto Water
Sandra Curot	Hydrogeologist, Umvoto Water
Andiswa Mlisa	Hydrogeologist, Umvoto Water
Dave Bredenkampf	Hydrogeologist, Independent Consultant
Simon Lorentz	Vadoze Zone Hydrologist, University of Natal
Julian Conrad	Hydrogeologist, GEOSS Groundwater Consultants
Bruce Kelbe	Hydrogeologist, University of Zululand
Talita Germishuyse	Numeric Modeller, University of Zululand
Kevin Petersen	Research Manager, Water Research Commission

Appendix 2:

Catalogue of Historical Data available on the Zachariashoek Research Catchments

Streamflow

Table 2A summarises the nature and period for which data was collected. Each of the five hydrological collected an extensive set of data.

Table 2A: Streamflow data available for the Zachariashoek research catchments.

Station	Dates available	
	Electronic (hourly, daily, weekly, monthly, yearly summaries)	Charts
Zachariashoek Bo (G1M17)	24/10/68 – 28/04/86	24/10/68 – 18/07/88
Zachariashoek Onder (G1M14)	24/10/68 – 29/12/94	24/10/68 – 18/07/96
Bakkerskloof (G1M18)	25/10/68 – 16/02/95	25/10/68 – 18/07/96
Kasteelkloof Bo (G1M15)	25/10/68 – 18/07/88	25/10/68 – 18/07/88
Kasteelkloof Onder (G1M16)	25/10/68 – 16/02/95	25/10/68 – 18/07/96

Rainfall

Rainfall data was collected from rainfall collectors distributed throughout the study site. The formt and the periods for which data was collected is presented in Table 2B. A summary of the position and the mean rainfall recorded for some of the rainfall collectors is presented in Table 2C. The position of the rainfall collectors can be seen in Figure 3.

Table 2B: Rainfall data available for the Zachariashoek research catchments.

Station	Dates available		
Zachariashoek	Electronic (hourly, daily, weekly, monthly, yearly summaries	On charts (*) or in electronic text format (~)	In field books and sheets
1B		~ 04/04/68 – 18/02/93	04/04/68 – 04/07/96
2B		~ 04/04/68 – 18/02/93	04/04/68 – 04/07/96
3A	25/07/68 – 01/02/96	* 20/06/68 – 18/07/96	
3B		~ 22/03/79 – 18/07/93	22/03/79 – 04/07/96
4A	01/01/93 – 10/11/94	* 20/06/68 – 18/07/96	
4B		~ 22/03/79 – 18/07/93	22/03/79 – 04/07/96
5B		~ 04/04/68 – 18/02/93	04/04/68 – 04/07/96
6B		~ 04/04/68 – 18/02/93	04/04/68 – 04/07/96
7B		~ 01/04/76 – 18/02/93	01/04/76 – 04/07/96
8B		~ 01/04/76 – 18/02/93	01/04/76 – 04/07/96
9B		~ 01/04/76 – 18/02/93	01/04/76 – 04/07/96

10A	30/07/81 – 05/11/81 01/01/93 – 10/11/94	* 25/03/76 – 18/07/96	
Wemmershoek dam		~ 01/10/80 – 30/09/87 (Available from DWAF)	

Table 2C: The rainfall gauges of the Zachariashoek research catchments, their periods of record and summarized catch.

Rain Gauge	Elevation (m amsl)	Period of data	MAP (mm)	Median AP (mm)	Proportion of rain Apr-Sept
1B	620	69.85	1101.6	980	76
2B	300	69.85	997.4	960	77
3A	800	69.85	1354.9	1321.1	77
3B	780	78.85	1390.8	1365.3	76
4B	300	78.85	1220.4	1146.4	77
5B	670	69.85	1624.4	1615.9	77
6B	300	69.85	1277.6	1251.5	78
7B	650	75.85	1662.3	1582.5	76
8B	500	75.85	1212.5	1109.2	76
9B	700	75.85	1304.8	1247.5	76

Water Quality

Weekly pH and Conductivity readings of grab samples were collected at 7sites sampling for period 21/01/71 – 13/09/90. Chemical analysis were also done on a monthly basis for samples taken from each of these sample points for period 04/03/71 to 05/01/89. The following characteristics were measured: pH, Conductivity, Na, K, Ca, Mg, Cl, SO_4, HCO_3, NO_3, PO_4, NH_4, F, Si, KN, TP. The suspended sediment concentrations were also measured in the weekly grab samples at Zachariashoek Onder, Bakkerskloof and Kasteelkloof Onder for the period 18/03/82 - 13/09/90. The suspended sediment concentration of samples taken during spateflow at Zachariashoek Onder, Bakkerskloof and Kasteelkloof Onder for period 07/03/83 - 20/09/90.

Groundwater

A summary of the periods over which water level readings were collected from the boreholes distributed throughout the study site is presented in Table 2D.

Table 2D: Groundwater data available for the Zachariashoek Research Catchments.

Borehole number and catchment name	Borehole collar elevation (m a.m.s.l)	Data on charts (with DWAF)	Data in field books (with CSIR)
1 (Zachariashoek Bo)	418.15	04/03/65 – 14/07/88	04/03/65 – 12/11/92
2 (Zachariashoek Onder)	293.06	04/03/65 – 12/11/92	04/03/65 – 12/11/92
3 (Bakkerskloof)	285.72	04/03/65 – 12/11/92	04/03/65 – 12/11/92
4 (Kasteelkloof Bo)	318.15	04/03/65 – 14/07/88	04/03/65 – 12/11/92
5 (Kasteelkloof Onder)	273.71	04/03/65 – 12/11/92	04/03/65 – 12/11/92
6 (Kasteelkloof Onder)	no info		04/03/65 – 12/11/92
7 (Kasteelkloof Onder)	no info		04/03/65 – 04/02/82
8 (Kasteelkloof Onder)	no info		06/05/65 – 26/06/73
9 (Zachariashoek Onder)	no info		08/04/65 – ± 1969 (Collapsed)
10 (Zachariashoek Bo)	no info		04/03/65 – 04/02/82
11 (Zachariashoek Bo)	no info		04/03/65 – 12/11/92
12 (Zachariashoek Bo)	no info		04/03/65 – 04/02/82
13 (Zachariashoek Onder)	no info		04/03/65 – 04/02/82
14 (Zachariashoek Onder)	no info		No data (dry)

Evaporation

Evaporation data was collected at the Zachariashoek research site, and is still being recorded at the Wemmershoek hydrological station. Table 2E summarises the type and period for which data is available.

Table 2E: Evaporation data available for the Zachariashoek Research Catchments.

Station	In electronic text format	On charts
Zachariashoek	09/04/81 – 10/03/93 (daily evaporation)	09/04/81 – 18/07/96
Wemmershoek Dam	Oct 1957 – ongoing (monthly evaporation)	

Other related WRC reports available:

A synthesis of the hydrogeology of the Table Mountain Group formation of a research strategy

Kevin Pietersen and Roger Parsons

A project was initiated during 2000 to synthesize the current knowledge about the Table Mountain Group (TMG) aquifer systems. This resulted in a document on the "Synthesis of the Hydrogeology of TMG – Formation of a Research Strategy". The document is subdivided onto technical papers and appropriate case studies. This exercise resulted in the understanding that to realize the potential of this groundwater supply, many uncertainties and barriers need to be overcome, including: deficient understanding of the occurrence, attributes and dynamics of TMG aquifer systems; lack of understanding of environmental impacts of exploitation; and uncertainties about how best to manage the resource within a multi-objective environment. Research of a multi-disciplinary nature is thus needed to find answers to questions concerning the water resource potential and optimal management of TMG aquifers, in the interest of furthering integrated water resource management in the region.

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Hydrogeology of the main Karoo Basin: Current knowledge and future research needs

AC Woodford • L Chevallier (editors)

A large part of South Africa (approximately 50% of the country as a whole) is underlain by the Karoo Supergroup of geological formations. A major characteristic of the Karoo Supergroup, which consists mainly of sandstone, mudstone, shale and siltstone. The majority of boreholes drilled in Karoo formations have very low yields . However, large volumes of groundwater are pumped from wellfields supplying towns, mines and the basements of buildings on a daily basis in areas underlain by the Karoo formations, which is not what one would expect from aquifers with a limited yield.

Karoo aquifers have a very complex and unpredictable behaviour. The general view is thus that Karoo aquifers are not reliable sources of water. However, there is no doubt that these aquifers played a significant part in the development of South Africa. This is evident in numerous place and area names, such as De Aar, Bitterfontein, Koffiefontein, Springfontein, Lelieput, Syfergat and Putsonderwater.

The Water Research Commission (WRC) has co-ordinated and funded numerous research projects aimed at understanding the hydrogeology, flow characteristics and exploitability of Karoo fractured-aquifers over the past 20 years. The research was conducted by various research institutions, governmental organisations and private consultants, involving both intensive localised and more extensive regional studies.

This document review and collate the vast amount of existing knowledge on Karoo fractured-aquifers and identify future research priorities.

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