GROUNDWATER RESOURCE EVALUATION IN TABLE MOUNTAIN GROUP AQUIFER SYSTEMS

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GROUNDWATER RESOURCE EVALUATION IN TABLE MOUNTAIN GROUP AQUIFER SYSTEMS

by

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DECLARATION

I declare that ***GROUNDWATER RESOURCE EVALUATION IN TABLE MOUNTAIN GROUP AQUIFER SYSTEMS*** is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledge by complete references.

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Signed…………….

ABSTRACT

Groundwater Resource Evaluation in Table Mountain Group Aquifer Systems

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PhD Thesis

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Keywords: groundwater resource evaluation, groundwater recharge, groundwater storage, groundwater discharge, groundwater/surface water interaction, GIS, 3D model, groundwater flow modeling, model calibration, Table Mountain Group

Table Mountain Group has been identified as one of the major regional aquifers in South Africa. With the outcrop area of 37000 km^2 mainly forming high rock mountains along the west and south coast and the deposit area of 248000 km^2 covering almost the whole Western Cape and part of Eastern Cape province, the well-indurated TMG has an average thickness of more than 2000 m. The vast distribution of it leads to a great diversity in its hydrogeological properties, which influences the dynamics of recharge, discharge and storage, resulting in groundwater occurrences unevenly distributed in TMG area. Thereby a proper regional groundwater resource evaluation, focusing on the quantification of recharge, discharge and storage, is of most importance for the efficient groundwater utilization and management of TMG aquifers.

Based on the previous researches conducted in TMG area, the regional groundwater resource of TMG is preliminarily but quantitatively classified using various approaches. The estimation of groundwater recharge is integrated from the results of different researchers and some of the results are assessed in a case study. As the main groundwater discharge from TMG aquifers, spring flow, groundwater abstraction and stream baseflow are quantitatively estimated. The former two components are accomplished by hydrocensus analysis. The surface water and groundwater interaction is also investigated, from which baseflow separations are performed to determine the magnitude of groundwater discharge into streams. The spatial distribution of the TMG aquifers (including Peninsula Aquifer and Nardouw

Aquifer), in both regional and vertical extent, is quantitatively estimated for the first time. This provides the foundation for both visualization of the aquifer geometry and the estimation of groundwater storage capacity. Different types of groundwater storage capacity, including total storage capacity, usable storage capacity, available storage capacity and sea level-related storage capacity, are demarcated and estimated for the TMG aquifers. A sustainable yield of $<1\times10^9$ m^3/year is proposed for the groundwater exploitation from the TMG aquifers based on the regional groundwater budget.

The response of TMG aquifer to pumping stress is studied in Kammanassie Mountains by groundwater flow modeling. 3D hydrogeological model is constructed, which helps to improve the understanding of the conceptual hydrogeological model. Detailed groundwater-related data analyses are performed on the basis of previous data sets. Groundwater numerical model is then established according to the conceptual model to simulate the aquifers responses to various pumping scenarios. Some general data processing approaches are also developed in this study that can be expected to apply to analog studies.

The expected result in this study is necessarily to be preliminary, outlining the groundwater utilization and management, and providing a starting point for more detailed and more realistic researches on basin and wellfield scales.

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1. Introduction and literature review

1.1 Introduction

Groundwater is one of the earth's most broadly distributed and most essential natural resources for municipal development, irrigation requirement, as well as industrial and domestic needs. Groundwater exits whenever water penetrates into the subsurface where the rocks are permeable enough to convey the water, and the infiltration rate is sufficient so that the rocks are saturated to a substantial thickness. Due to the difference in hydraulic or piezometric heads, the movement of groundwater occurs through a single or multiple heterogeneous geologic formations. These formations generally include permeable units regarded as water bearing zones or aquifers, and less permeable units which were previously considered as confining zones or aquifuges but now are more commonly known as semi-confining zones or aquitards (Freeze and Cherry, 1979). Groundwater becomes a valuable resource when the water discharges from water-bearing zones yields useful supply to wells, springs, or streams, when the discharged water is perennial or seasonally persists long enough to meet a specific requirement, when the mineral substances dissolved by water as it penetrated through rocks do not reach much concentration to make the water unfit for desired use, and when the practical exploitation of the groundwater in an area does not cause environmental problems such as over depression of water table, degradation of vegetation or wetland, or encroachment of sea water, etc. While the patterns of surface water flow are generally known and the potential of the surface water reservoirs on principal rivers has extensively evaluated, there has been very limited studies of groundwater resources. In other words, groundwater has more significance in the arid or semi-arid areas, like most of the Africa.

In the hydrologic cycle, groundwater is a renewable resource ultimately fed by precipitation. Meteoric water goes into aquifers as natural recharge and groundwater exits from the aquifer as natural discharge, which forms a dynamic system. The system can be assumed in a naturally steady state before groundwater development, where the recharge is balanced by natural discharge. Any change in operation of one part is reflected in more or less substantial changes in other parts, and the whole system may evolve towards a new steady state. This state is achieved when the abstraction of the wells is balanced by the increased recharge, decreased natural discharge, or the combination of the two. The sum of the diverted discharge and induced recharge is called the "capture" of wells. When analyzing groundwater system, consideration must be given to both the natural flow system and the effective groundwater withdrawals on such things as the storage of aquifer system, the mode of groundwater recharge and discharge, the fluctuation of groundwater levels in nearby wells or wetland, and the response of flow in nearby streams due to natural groundwater discharge and artificial disturbance to the aquifer system. The need is to understand input-and-output or cause-and-effect relationships well enough to enable to propose possible assessments for development and management choices, considering the complexity of factors. For a sustainable development of water resources, it is imperative to make a quantitative estimation of the available groundwater resources other than just in qualitative terms. The estimation should be under the consideration as to maintain the groundwater reservoir in a state of dynamic equilibrium over a period of time and the water level fluctuations have to be kept within a particular range over the dry and rainy seasons.

Many aspects of hydrogeological studies have been evolved, ranging from hydrothermal assessment to aquifer contamination prevention, the most advances have been in those studies of the feasibility of groundwater resources to support fresh water supply in various scales (Zektser, 2000). These advances have far-reaching effects on the techniques of groundwater investigation, the methodology of water resource evaluation, and the potential for efficient management of groundwater resources. As quantification of groundwater resources requires proper understanding of the behaviors and characteristics of aquifer system which functions as both flow path and storage of groundwater, the impact of a variety of factors on the evolution of groundwater resources should be taken into account in detail to refine the conceptual understanding of the underlying geology and the mechanism that affects groundwater resources (Mulhall and Demicco, 2004). The mechanism of groundwater storages, depending on the geometric and physical properties, and the recharge and discharge processes of the aquifers, is different in various aquifers, particularly in fractured rock aquifers of which the anisotropic properties are allover and extremely difficult to determine. Therefore, the estimation of groundwater storage or storage capacity and sustainable yield on a regional scale is recently more convenient to estimate by using the existing volumetric models with the average storativity or specific yield values. Also, the estimation should be based on the consideration of the three dimensions of the aquifer geometry, the effects of groundwater withdrawal, recharge and discharge on the groundwater system as the whole.

The significance of groundwater and surface water interaction has been given more attentions from many hydrogeologists (Nathan, 1990; Winter et al., 1998 Chapman, 1999; Xu, 2002; Hughes et al, 2003) in recent decades. Intensive groundwater abstraction can affect the relationship between surface water and groundwater regimes, such as the depletion of stream water quantity and quality, resulting in the stream water flows into the nearby aquifers. The majority of groundwater/surface water interactions have been frequently observed to occur on such a type of stream-aquifer system as the groundwater discharges into stream water, particularly in mountain areas. In regional groundwater resource estimation, the developments of baseflow concept and associated methods have provided important understanding and useful tools to study such relationships. Although the baseflow separated from each stream flow with long-term monitoring data cannot completely accounts for the groundwater discharges into the stream flow, however, it roughly represents that amount from aquifer storage if the interflow is not considerable then could be overlooked.

The subsurface flow system is usually more complex. It may be desirable to predict the behavior of an aquifer through borehole operation, the effects of recharge, discharge and solid boundaries, flow and transport in an anisotropic medium on the groundwater system. Groundwater models are recently the more convenient tools in such predictions. A model is a simplified version of a real groundwater system that approximately simulates the complexity of reality, and is used to simplify the reality in a manner of capturing or representing the essential features and processes associated with groundwater problems. To grasp groundwater problems, model assumptions and simplifications are often required. The simplification is introduced in the form of a set of assumptions that express the understanding of the nature of the system and its behavior (Bear and Verruijt, 1987). Currently, for solving groundwater problems the most commonly used methods in groundwater modeling are the numerical models as finite difference and finite element (Wang and Anderson, 1982). The simulation of groundwater model can be used to improve the understanding of complex hydrogeological condition and the results of model computation can be used to refine and optimize the exploration designing and used for handling a convenient management plan of groundwater abstraction on a sustainable basis.

1.1.1 Problems and objectives of the study

In South Africa, the major aquifers with the capacity of bulk water supply mostly consist of fractured rock formations, such as dolomite in northern areas, Karoo dolerite, and Table Mountain Group (TMG) sandstones distributed in the Western and Eastern Cape provinces. Groundwater accounts for the second of the total amount of water withdrawn from all water resources in the nation, but the study of such natural resources has been predominant in problem areas and has been largely concerned with wellfield development associated with water supply, water quality evaluation and contamination remediation, and falling of groundwater level. More detailed studies in limited areas have clarified a few of the complex nature of groundwater reservoir. In spite of the national scenario on the availability of groundwater being favorable, there are actually many areas in the country facing scarcity of water. This is because of the unplanned groundwater development resulting in fall of water levels, failure of wells, and salinity ingress in coastal areas. The development and over-exploitation of groundwater resources in certain parts of the country have raised the concern and need for judicious and scientific resource management and conservation.

Prior to the late 1980s, groundwater development in the TMG aquifers was restricted to the areas with water shortages. It is not more than a decade that the groundwater in the TMG sandstones has received greater attention in the area of agricultural activities, and municipal and domestic development. As the aim of groundwater investigation is currently not only to establish the well fields to provide significant supplies to help alleviate future shortages, but also to see the potential ecological impact of large-scale groundwater use. Consequently how much groundwater stored and how this water distributed in the TMG area become very essential. A comprehensive and quantitative estimation of this water resource has not been done yet on a regional scale, although all the previous studies have given some rough estimates. Accordingly, the following objectives are expected in this study:

1) Understanding the concept of groundwater resource and methodology of groundwater resource evaluation based on the hydrogeological setting.

2) Regional evaluation of the TMG groundwater resources involving the quantification of recharge, storage and discharge and the proposition of sustainable yield based on groundwater budget for the regional aquifer system.

3) Quantitative analyses of the stream-aquifer interaction of TMG, attempting to work out the most important component of groundwater discharge in the area.

4) Groundwater flow modeling in Kammanassie Mountains, aiming to simulate the TMG aquifer response to pumping.

5) Development of applicable data processing approaches that may be used in analog studies.

The abovementioned objectives can only be made with an enriched knowledge of hydrogeology together with geology, geomorphology, and climate information of TMG. Analysis of these data requires the application of GIS techniques and some of the works have to be done by programming based on relevant softwares. In view of groundwater as a resource, the relationships between recharge, storage and discharge are also addressed in this study for the interest to have a full understanding of the dynamic characteristics of it and to manage it. This study would contribute a lot to the sustainable development of the "buried treasure" of TMG groundwater resource.

1.1.2 Outline of the thesis

The structure of this dissertation has been made in correspondence with the development of the study. It begins with a brief background to this study and the objectives expected to be made in this study. The related research in study area has been reviewed in Chapter 1. In Chapter 2, the concept of groundwater resources and methodology of groundwater resource evaluation is introduced. The background of TMG aquifer stream is addressed based on the description of geology and hydrogeology settings in Chapter 3. Chapter 4 and Chapter 5, as the main part of this thesis, deal with the groundwater resource evaluation and the groundwater/surface water interaction of TMG aquifers respectively. The response of TMG aquifer to pumping in Kammanassie Mountains is studied with numerical simulation in Chapter 6. In Chapter 7, a comprehensive summary is made, a brief conclusion is drawn, and the suggestions for further studies are also recommended. The dissertation ends with the references.

1.2 literature review

1.2.1 The historical background of hydrogeological significance of TMG

The significance of TMG as a regional aquifer has been overlooked for a long time. The recognition of it has gone through a experiences of many negative opions, which can be traced back to 1937 (Weaver, 2002), in a report of Geological Survey, TMG was mentioned as "of little importance from the boring aspect" because of the fast drainage by the streams or springs issued from the structures. The situation may also be reflected by Du Toit (1954), who thought that the low porosity of the rock matrix and the high transmissivity of the fractures left little chance of the groundwater potential. Even very recently, TMG was still regarded as having "no great importance as a regional aquifer" (Weaver, 2002) and only the shallow groundwater in the fractures could be exploited by farmers. Unquestionably, these viewpoints imposed a negative effect on research and investigation work in the TMG aquifer systems, in turn impeded its exploration and exploitation. Quite a few proposals for study in TMG aquifer had been turned down time by time.

Fortunately situation was changed in 1995 when Prof. Arie S. Issar, the Israeli hydrogeologist visited the first high-yielding artesian borehole targeted for deep groundwater in Peninsula Aquifer. He said, "It can be foreseen that the drilling of deep wells, of a diameter big enough to enable the pumpage of large quantities of water is going to play an important role in the future development of the water resource of the Republic of South Africa. As this requires special investments in equipment and know how, it can be justified only if it involves a rather large number of wells". (Issar, 1995). From his statement, the previous lack of interest and belief in TMG as a regional aquifer was partly because of the limitations of drilling techniques and equipment of the time.

From 1997, with the acceptance of CAGE (Citrusdal Artesian Groundwater Exploration) project for DWAF and a workshop on TMG experience initiated by Weaver, the TMG aquifer started to get the suppose-to-be recognition to be a potential groundwater resource on a regional scale. The recent activities around the hydrogeological significance of TMG include: a TMG-focus in IAH2000, TMG researches funded by WRC (Water Research Commission of South Africa) in 2000, a workshop in 2001 held by WRC focusing on identification of TMG research priorities and the WRC issued publication (Pietersen and Parsons, 2002) on existing TMG knowledge in 2002, etc. Two research projects were committed by WRC in 2003 with University of the Western Cape, viz. 'The recharge estimation in the Table Mountain Group (TMG) aquifer systems' and 'The flow conceptualization and storage determination in the Table Mountain Group (TMG) aquifer systems'.

1.2.2 Regional groundwater resource evaluation of TMG Aquifers

1.2.2.1 Recharge estimation

Wu (2005) has made a detailed overview of recharge estimation in TMG area as listed in Table 1-1, summarizing the TMG recharge studies conducted in the past ten years. It can be observed from Table 1-1 that the estimates vary a lot from place to place with a wide range of groundwater recharge from 0.3% to 83%. Moreover, even in the same place, the estimates change greatly with the methods applied, e.g. in Vermaaks River the groundwater recharge varies from 0.3% to 43.5% for Nardouw sandstones and 2.7% to 23.9% for Peninsula formation (Kortze, 2000; 2002), respectively.

Wu (2005) presented an integrated recharge rate of 1.65-3.30% in Kammanassie area by assigning different weight values to the estimation results derived from different methods. He estimated the spatial distribution of recharge rate using water balance approach and an average recharge of 29.74 mm over TMG outcrop area was derived.

In this study, a soil water balance approach is used to estimate the recharge potential in TMG area, which will be introduced in Chapter 4.

Table 1-1 Review of recharge estimates in the TMG area (after Wu, 2005)

Place	Method	Aquifer	MAP (mm)	Recharge (%)	Source
Vermaaks River	Base flow	Peninsula	560	8.9	Bredenkamp, 1995
	Unknown	Peninsula	299-714	17	
	CMB	Nardouw / Peninsula		43.5/11.1	Kortze, 2000 and 2002
	SVF			3.1/19.7	
	SVF (fit)			3.4/16.4	
	CRD			3.2/14.4	
	Base flow			21.4/12.5	
	EARTH			2.9/23.9	
	^{2}H Displacement			0.3/2.7	
	^{14}C Age			1.8/2.0	
	GIS raster	TMG		2.5/4.8	Woodford, 2002
	CMB			5	Weaver et al., 2002
Langebaan Road Field	CMB	Bredasdorp	396.4-648.9	9.7	Weaver and Talma, 2002
	CMB			11.2	
	CMB			13.5	
	CMB			11.5	
Greater Oudtshoorn	Empirical	Peninsula	165-1049	14	Hartnady and Hay, 2002
	Empirical	Nardouw		7	
Struibaai	CMB	TMG	436	17.4	Weaver and Talma, 1999, 2002
Agter Witzenberg	CMB	Nardouw	579-777	50,44	
Botriver		Nardouw	477-1546	20	
Hermanus	^{14}C		635	22(20-24)	Rosewarne and Kortze, 1996
Uitenhage Artesian Basin	Spring flow		298-1203	10	Kok, 1992
	CMB	Groot Winterhoek		25	Maclear, 1996
	CMB			55	R Parson, 2002
Whole TMG (within a radius of 200Km from Cape Town)	GIS	13200Km^2 outcrop	600-2020	33	Weaver and Talma, 1999, 2002
CAGE: Low rainfall	GIS	Low lying	286-371	8	Hartnady and Hay, 2000 and 2002
CAGE: High Mountain		TMG		23	
CAGE: Mountain area				30-40	
CAGE	Isotopes			50	Weaver et al., 1999
Uitenhage, Coega aquifers	WB	TMG	460	83	Kok, 1992
	CMB	TMG	250-850	24-55	Maclear, 1996
	WB			11	Bredenkamp, 2000; Xu and Maclear, 2003

1.2.2.2 Storativity

Storativity is the general term of specific yield (in the case of unconfined aquifer) and storage coefficient (in the case of confined aquifer). In most of the TMG studies, specific yield and storage coefficient are not separated clearly and therefore the term storativity is commonly used to describe the aquifer storage properties.

A storativity of <0.001 is generally assigned to the TMG Aquifers on the WRC "Saturated Indices" map (Vegter, 1995). Another general storativity estimation of TMG is provided by Rosewarne (2002), who thinks that a figure of 0.001 is a fair estimate for a bulk storativity of the Peninsula and Nardouw formations. Rosewarne (2002) summarized some estimates of storativity adopted by several researchers for various TMG formations and different TMG areas (Table 1-2). There are other previous estimates of storativity of TMG that are higher than 0.001, as quoted by Weaver (2000) as follows:

- Weaver (2000) uses a storativity of 10^{-2} to estimate the groundwater reserve in TMG within a 200km radius of Cape Town;
- Hartnady and Hay (2001) support a storativity of 10^{-1}, and
- Kotze supports 10^{-2} to 5×10^{-2} (Kotze, 2000)

Table 1-2 Storativity values for various TMG formations and areas (after Rosewarne, 2002)

Area	Formation	Reference	Storativity	Analysis method
Citrusdal	Peninsula	Umvoto-SRK (2000)	1×10^{-3} to1×10^{-4}	FC∗
Struisbaai	Peninsula/Nardouw	Weaver (1999)	8.6×10^{-3}	Jacob
Uitenhage	Peninsula/Nardouw	Maclear (2001)	2×10^{-4} to5×10^{-2}	Unknown
Kleinmond-Bot River	Nardouw	Parsons (2001)	1 to 5×10^{-4}	Jacob and FC
Klein Karoo	Peninsula/Nardouw	Kortze (2000)	1×10^{-4} to1×10^{-2}	FC
St Francis-on-sea	Nardouw	Rosewarne (1989)	1.8×10^{-3} to 3.3×10^{-3}	Gringarten & Witherspoon
∗ Flow characteristics method				

Van Tonder and Xu (1999) suggest that the storativity of the highly permeable fractures are usually very low in the order of 10^{-4} to 10^{-7}, whilst that of the matrix is much higher (i.e. 0.005 to 0.05). They also stated that the storativity (S) should be the sum of the storage coefficient (S_c) of the fractured rock aquifer and the specific yield (S_y) of the fracture, i.e.:

$S = S_c + S_y$

Woodford (2002) described the storativity of a pumped fracture by an explanative figure and summarized the storativity values obtained by pumping tests on various TMG sites. He stated that storativity of a fracture in a pumping process is complex and varies spatially and temporally.

Hartnady and Hay (2000) obtained storativity values from Aquifer-Tests conducted in the Boschkloof Wellfield, Citrusdal using RPTSolv Software and FC-Method. The results ranged from 1.1×10^{-5} to 4.6×10^{-3} for five boreholes. Based upon the results of the aquifer-tests, they recommended an a priori storativity value of 10^{-3} for the deeper confined part of TMG aquifers and for the upper the range of 10^{-5} to 10^{-3} could be given.

Kotze also did aquifer tests in the little Karoo area and FC-method and Cooper-Jacob method were used to estimate the hydraulic properties. She estimated the storativity to be 1.0×10^{-3} to 2.2×10^{-3} by FC-method, which is in accordance with Hartnady and Hay (2000).

1.2.2.3 Quantification of Groundwater resource potential in TMG aquifers

The significance of TMG aquifers is evidenced by the occurrence of hotsprings issued from them. However, the conceptual understanding of the highly fractured aquifer on a regional basis is still scarce. This is partly because of the extensive distribution of the aquifer in both regional and vertical extent and the associated large spatial varieties of the hydrogeological properties. The other reasons may be attributed to the practical difficulties of deep drilling. These make the quantification of groundwater resource potential in TMG aquifer very difficult. Nevertheless there are still some rough guesses and estimates of the water quantity in TMG Aquifers on a regional scale (Hartnady, 2002; Weaver, 2002), most of which were roughly determined by approximate calculation of the aquifer volume and the storage characteristics.

The earliest regional analysis of TMG resource potential was probably made by the "Western Cape System Analysis" (WCSA), which dealt with only 948km^2 TMG outcrop area in Berg River, Palmiet River and Riviersonderend catchments (DWAF, 1993). The estimate was carried out by calculating the baseflow component of the mean annual runoff (MAR) as about 300Mm^3/yr in the abovementioned areas. Hartnady et al. (2002) assessed the WCSA estimate and pointed out that their study only considered the storage of upper 200m of the "saturated thickness" and overlooked the much more significant and deep-buried part of groundwater, which requires high drilling capacity. Consequently they gave a rough estimate of about 2000Mm^3 groundwater reserve for Peninsula Aquifer in the same area with the fracture porosity for upper continental crust of 0.1% (Brace, 1984) and predicted that an area-averaged drawdown of 10m associated with the abstraction of 150Mm^3/yr would be acceptable by taking into account the technical feasibility and the possible impact on the environment. They extended this result to the whole TMG aquifer and concluded that a maximum potential groundwater volume of 10^{11} to 10^{12} m^3 could be expected.

Weaver (2002) stated that there are no confining units in the TMG on a regional scale except for the local conditions where Bokkeveld Group or Cedarberg Formation overlies TMG. In accordance with Van Tonder and Xu (1999), Weaver (2002) thought that the available water from the TMG is a combination of both storativity and specific yield ($S_c + S_y$), and varies on a regional scale, from which he estimated that the groundwater potential from TMG is in the order of 0.5%, or in the range of 5% (unconfined aquifers) to 0.05% (confined aquifers).

Another summary of TMG storage estimation was provided by Rosewarne P (2002). A rock volume of 47000 billion m^3 was derived by using a rough dimensionless analysis of the TMG outcrop area and thickness. With the combined consideration of the regional water table, he concluded that there are tens of billions of cubic meters of groundwater in storage in the TMG aquifer and 1.5 billion m^3 in existing dams sourced from the TMG runoff water.

1.2.2.4 Groundwater use from TMG aquifers

Groundwater abstraction from TMG is distributed over the associated area, from Olifants/ Doring in the west, Berg and Breede in the south to the Gouritz and the Fish/ Gamtoos in the east, according to the Water Management Areas of the Department of Water Affairs and Forestry (DWAF, 2002). Though widely spread, most of the groundwater exploitation is localized and concentrates on points of consumption, which mainly includes utilization by municipalities, irrigation, holiday resorts and some minor farm users. The current groundwater use occupies a very small proportion of the overall water supply, i.e. about 5% (DWAF, 2002). Since surface water has been used to the maximum limit in most areas, this is much potential for the further development of TMG aquifers. More than 30 major users of TMG groundwater have been identified, such as Steytlerville, Jeffreys Bay, St Francis Bay, Humansdorp, Bredasdorp, Struisbaai, Botrivier, Lamberts Bay, Leopoldville, Graafwater and etc. The annual abstraction is commonly over 0.1 Mm^3 and in some towns even exceeds 11Mm^3. Nakhwa (2005) summarized the major towns using groundwater from TMG Aquifer as listed in Table 1-3.

Table 1-3 Groundwater use from the TMG (after Nakhwa, 2005)

AREA/TOWN	AMOUNT(Mm^3)	USE	YEAR
Albertinia	0.1	urban	1999
Brandvlei-Sandrift	11.0	irrigation	2001
Bredasdorp	0.5	urban	2001
Calitzdorp	0.1	urban	2001
Ceres basin	8.0	irrigation	2001
Dysselsdorp	2.3	urban	1999
Humansdorp	1.1	urban	1998
Jeffreys Bay	1.8	urban	1998
St Francis Bay	0.55	urban	1998
Struisbaai	0.3	urban	2001
Toverwater hot spa	0.36	recreation	1999
Uitenhage	5.7	irrigation	1998
Vanwykdorp	2.3	irrigation	1999
Witzenberg valley	11.0	irrigation	2001

1.2.2.5 Case studies of exploitation in TMG aquifer

With the gradual recognition of groundwater significance of TMG Aquifer, a number of studies focusing on research or exploitation have been conducted and are ongoing in wide associated areas. Some of these study areas include the Agter-Witzenberg Valley, Arabella, Botriver, Ceres, Boschkloof, Hex River Valley, Blikhuis, Olifants River Valley, the Klein Karoo rural water supply scheme (KKRWSS), Uitenhage Artesian Basin, Koo Valley, and etc in the Western Cape and Plettenberg Bay, Steytlerville, Port Elizabeth Municipal area, St Francis-on-sea, and etc in the Eastern Cape (Pietersen and Parsons, 2002). Many contributions and experiences have been accumulated from these studies. The present and future development of the aquifer is crucially linked to the problem of insufficient knowledge of the dynamics and characteristics of the groundwater and its exploitation.

1.3 Summary

Since groundwater resource is one of the most valuable resources on the earth, the study of it has gone through a long history for the purpose of utilizing and managing such resource in a sustainable manner, among which the most efforts are associated with the quantitative and qualitative assessment of groundwater for the purpose of fresh water supply in various scales.

TMG has been identified as a one of the major fractured aquifers in South Africa. But the comprehensive assessment of this aquifer system on a regional scale is still left blank except some rough estimates. The following objectives are expected to achieve in this study:

1) General concept of groundwater resource;

2) Regional groundwater evaluation of the TMG groundwater resource;

3) Groundwater – surface water interaction in TMG aquifers;

4) Pumping effect on TMG aquifer system; and

5) New data processing approaches applicable to analog studies.

A lot of previous TMG-related researches, concerning the historic background, recharge estimation, groundwater use, aquifer properties and etc., are reviewed and summarized, which constructs the foundation of this study.

2. Definition and classification of groundwater resource

2.1 Definition of groundwater resource

The earth is the only planet in the universe that we, human being can live on so far. From the space it looks like a “blue ball” because 71% of its surface is occupied by sea, while only 29% by land, on which large amounts of rivers and lakes are developed. According to some anonymous specialists, the whole storage of water on earth is about 1.386×10^{18} m^3, which would amount to 3000 m above the surface of the earth if it were averagely covered by the water. From this point the conclusion can be made that enough water is available on the earth. However, appeals from all over the world are about the shortage of water. The reason is simple, water does not equal to water resource.

Rees (1985) gives a clear definition on resource in one of her famous books − Natural Resources Allocation, Economics and Policy. In this book she defines that resource is the available source of wealth, a new or reserved supply that can be used when needed, and could only be decided by human being but not by the nature. The concept of resource implies that human make assessment of the natural environment based on specific objectives that work for them (Ciriacy, 1952). Mankind has been exploring the nature for generations and evaluating the value of organic and inorganic substance from the nature. Any substance must meet two requirements to be defined as resource. The first is that the knowledge and technology of utilizing it is available, the second is the demand for the substance. With the dissatisfaction of any one, the natural substance can only be termed neutral material rather than resource (Zimmermann, 1951).

The definition of resource is dynamic (Lowe and Goyder, 1983). With the enrichment of knowledge and the development of technology, culture and civilization, the definition of resource has been changed a lot. What is regarded as a resource today was probably not in the Paleolithic Age. A kind of substance that is considered to be a highly valued resource in one social ideology may be just a neutral material in others. Something is resource to somebody, but is only obstacles or nothing to others. For example, a swampland may be an important nature reserve, however, it reduces the production of farmers.

Resource can be classified into two groups, renewable resource and unrenewable resource (Fisher, 1981). Strictly speaking, all resources are renewable, but different in the context of time. The classification is based upon the time scale.

According to the definition of resource, obviously not all water on the earth is water resource. At the current knowledge and technology level, the most important water to human being is fresh water (WMO, 1997). Unfortunately only 2.5% of the water on the earth is fresh water, while 2/3 of which has been limited to icecap or glacier. For the rest 1/3, 20% is located far from people's living area, while most of the 80% often comes with the flood or storm on the wrong time or in the wrong place and can't be effectively utilized by human being. Eventually there is only a tiny part of fresh water that can be directly obtained by people on the earth and be regarded as water resource. It's no wonder that the water shortage occurs on the earth.

Water resource can be divided into surface water resource and groundwater resource. Surface water includes water from rivers, lakes, glaciers and swamps. Groundwater is usually referred to the subsurface water that occurs beneath water table in the fully saturated soils and geological formations (Freeze and Cherry, 1979). Groundwater is recharged by the infiltration of rainfall and surface water, discharged by stream flow, evaporation and subsurface flow.

The concepts of groundwater and groundwater resource are different in that groundwater refers to all the subsurface water, which is possibly a large amount and very difficult to be quantified. Actually the extensive subsurface space on the earth may be considered as a huge groundwater reservoir, in which the groundwater is usually grouped into two parts according to the respective renewable velocity, one part is mobile or renewable and the other is relatively immobile or unrenewable. The premises of groundwater as a resource should be: i) the existence of water bearing space, namely aquifer, ii) the recharge condition, and iii) technical feasibility of groundwater exploitation. Currently the groundwater resource that we have recognized is the renewable part under the condition of natural depletion and human exploitation on a relatively short time scale. The problem arises from the close relationship of the two parts. The extract of the lower storage in the groundwater reservoir will have effect on the upper recharge, and the quantity of groundwater resource is changed with the groundwater abstraction.

2.2 Classification of groundwater resource

Many types of classification of groundwater resource have been developed in many countries based on their own knowledge and experience. The author has gone through numbers of literatures but could not list all of them. Two types of systematic classifications are introduced here.

2.2.1 Four-storage classification

The term storage and the four-storage classification were proposed by Pulotenikov (Плтников, 1959), and were widely used in groundwater resource evaluation in Russia and China. Storage is supposed to be a relatively stable quantity stored in a specific space. However groundwater is different from solid mineral resources or other liquid resource (like petrol) in that it is mobile and renewable. Groundwater exists in the interspaces of rock, not only occupying the space, but also varied temporally with the process of recharge and discharge. Therefore storage, as a single word, is too simple to reflect the complexity of the relationship between the elements in a hydrological cycle. In the past storage was grouped into four classes in groundwater resource evaluation, which are static storage, mobile storage, adjustable storage and exploitable storage. The definition of the four classes of storage and the limitations are delineated as follows.

Static storage

The static storage or permanent storage is defined as the volume of groundwater below the lowermost water table, which is traditionally expressed as:

Unconfined aquifer: $V_s = \mu V$ (2-1a)

Confined aquifer: $V_s = SV$ (2-1b)

Where μ is the specific yield, S the storage coefficient of the aquifer, and V is the volume of the aquifer. According to kinematics, the static storage should be the volume of groundwater below the local discharge datum plane, in that the static storage is not the volume of immobile water but the minimum storage in a hydrometeorological cycle, varying with the change of recharge or discharge. As a matter of fact there is no absolutely static storage on a stable sustainable recharge condition unless the lowermost water table doesn’t occur periodically but always towards the direction of the decrease of the groundwater volume. When the water table in aquifer declines to the discharge datum plane, the movement of groundwater stops and the volume of the groundwater keep unchangeable, which accords with the concept of “static”. Nevertheless this is a particular condition that the discharge datum plane keeps immoveable.

Mobile storage

Mobile storage is the natural flow rate (Q) of groundwater passing through the cross section of the aquifer, calculated by Darcy Law:

$Q = KBHI$ (2-2)

Where *K* is the conductivity and *I* the groundwater gradient of the aquifer. This expression simply demonstrates the flow rate of groundwater on a specific time and in a specific space, without reflecting the variance of the water flow rate with the change of time and space. It is unreasonable to use a point data to represent the whole aquifer. Both of the hydraulic gradient, and the aquifer's thickness *H* are not constant and vary with the condition of recharge and discharge, the location of the cross section and the time. As a result the mobile storage is not a constant. For unconfined aquifer, the longer flow distance may be associated with the larger recharge area and higher recharge potential from rainfall infiltration. If the cross section is located at the groundwater watershed where the flow distance and the recharge area is zero geometrically and no recharge or discharge occurs, the mobile storage is definitely zero. When the cross section moves to the lower course along the flow distance, the mobile storage will increase with the increase of the recharge area. On a particular condition when the cross section is located on the discharge datum plane where the recharge area is the maximum, the maximum mobile storage is also achieved and equals to the groundwater discharge in this place. Such condition may be used to determine the recharge of the aquifer inversely if no other route of discharge exists.

Adjustable storage

Usually the adjustable storage is defined as the groundwater volume between the highest and the lowest water table during a hydrological year.

$$V_a = \mu A(h_{\max} - h_{\min}) \quad (2\text{-}3)$$

It is well recognized that before the rainfall infiltrates to groundwater, the water table could reach the lowest (h_{min}) in the aquifer while after the rainfall infiltration the water table is elevated gradually till the highest (h_{max}) on some time after the rainfall stops to recharge the groundwater. Even the uppermost water table is not a constant, but varies with the flow distance. In most cases the adjustable storage is not the whole recharge quantity of the aquifer but part of it, which stagnates in the aquifer during the wet reason and will continue to discharge as mobile storage as soon as the rainfall ceases. From this point the adjustable storage is essentially a composing part of the mobile storage and it may lead to error to regard both of them as independent quantities.

Exploitable storage

Exploitable storage is the groundwater that can be extracted from the aquifer on some conditions. It is based on the feasibility of exploitation of groundwater resource and has a close relationship with the exploitation technique. It should not be coordinate with the dynamic storage, static storage and adjustable storage, neither the sum of them. It is related to the abovementioned three types of storage and also depends on the exploitation facilities, position, scheme, and etc. The concept of exploitable storage in a natural condition doesn't apply to the exploitable storage in a condition when the relationship between recharge and discharge is changeable during the progress of exploitation.

To evaluate groundwater resource, it should be considered that as part of the earth hydrosphere, groundwater has a close relationship with atmosphere, surface water and vadose zone and they can be inter-transmitted.

2.2.2 Alternative basin yields

In *Ground Water Management* compiled by American Society of Civil Engineering in 1972 (ASCE, 1972), several concepts of basin yields are introduced. They are briefly expatiated in the following.

Sustainable yield

Sustainable yield is used to express the amount of water an aquifer or well can yield for consumption in a sustainable manner without producing unacceptable negative effects. Potential unacceptable effects include contamination of the aquifer water by induced infiltration, seawater intrusion, decreased river flows, lowering of the water table, land subsidence, and etc.

Mining Yield

Mining yield represents the situation that groundwater abstraction rate exceeds the recharge rate, which must be limited in time until the aquifer storage is depleted. There have been many controversies on the practical feasibility of mining yield since it was proposed. One argument raised by the supporters is that water in storage is of no value unless it is used. They prove their argument by providing the example of Sahara Desert, where groundwater resource is the only available water resource and any use of groundwater is mining of it. However the abstraction must be made to maintain the basic requirements and it may sustain for several decades to centuries with proper management.

Sustained Yield

Sustained yield is the yield of the group of wells in watercourse aquifer, which is usually buried in the floodplain of a large river system and has hydraulic relationship with modern river. Sustained yield specifies the minimum yield of group of wells constructed in the alluvial aquifer under all the conditions of river flow. It is not a constant even no any artificial recharge has been fulfilled.

Perennial Yield

The perennial yield of a groundwater basin defines the rate at which water can be withdrawn perennially under specified operating conditions without producing an undesired result. Any draft in excess of perennial yield is referred to as overdraft. Existence of overdraft implies that continuation of negative impacts on environmental, social, or economic conditions.

Deferred Perennial Yield

There are two different pumping rates in the concept of deferred perennial yield. The aquifer is firstly pumped at a rate exceeding the perennial yield; thereby the groundwater level is reduced. The overdraft at the first stage should be planned properly without producing any undesirable effects. After the groundwater level has been lowered to a certain depth, a second rate close to the perennial yield is applied to the pumping to keep the balance between recharge and abstraction. With a larger available storage volume in the second pumping stage, more water can be recharged and a larger perennial yield can be obtained.

Maximum Perennial Yield

The maximum perennial yield means the maximum quantity of groundwater perennially available if all possible methods and sources are developed to recharge the basin. This quantity depends on the amount of water economically, legally, and politically available to the organization or agency managing the basin. Clearly, the more water that can be recharged both naturally and artificially to a basin, the greater the yield.

2.2.3 Recharge, storage and discharge

Groundwater can be regarded as resource in that it has the value to be exploited both qualitatively and quantitatively. Groundwater resource evaluation should be based on the estimation of recharge, storage and discharge. A comprehensive assessment is required on the quality and quantity of groundwater resource. This type of classification has been extensively adopted in Japan, China and etc. It is still being effectively utilized in many countries. In this study, this classification is adopted to evaluate the groundwater resource in TMG aquifers.

2.2.3.1 The concepts of recharge, storage and discharge

1) Groundwater recharge

Groundwater recharge is the water entering the aquifer from various sources with the dimension of L^3/T. It includes the infiltration of rainfall and surface water, groundwater influx from other hydrogeological unit, leakage from other aquifer units and artificial recharge.

According to the type of source, recharge is further divided into natural recharge, induced recharge and artificial recharge.

The sources of natural recharge include precipitation, streamflow, lakes, reservoirs, and the groundwater influx from adjacent hydrogeological unit or aquifer under the natural conditions. Prior to development the natural recharge is usually balanced by natural discharge via baseflow, evaporation, spring and etc on a long-term basis.

Induced recharge is the extra recharge during groundwater exploitation, including the capture of surface water, additional leakage from adjacent aquifer due to the exploitation depression cone, the expansion of recharge zone resulted from the movement of groundwater watershed with the development of exploitation. The induced recharge may be surface water or groundwater from adjacent unit or aquifer, which does not take part in the water balance of the studying aquifer unit and can only be captured after the exploitation changes the hydrodynamic condition. Therefore induced recharge is different from natural recharge in that its quantity not only depends on the hydrometeorological and hydrogeological condition, but also varies with the exploitation conditions. Generally the captured recharge increases with the scale of the exploitation.

Artificial recharge is defined as augmenting the natural movement of surface water into underground formations by some method of construction, by spreading of water, or by artificially changing natural conditions (Todd, 1980).

2) Groundwater storage

Groundwater storage is the volume of gravitational water stored in an aquifer or aquifer system with the dimension of L^3. Under a certain buried condition, two terms, volumetric storage and elastic storage are adopted to delineate two different kinds of groundwater stored in aquifer. The former is specified as, under the barometric pressure, the quantity of gravitational water stored in the interstice of an aquifer, while the latter describes such a condition that when the natural pressure, which initially exceeded the atmosphere pressure, reduces to barometric pressure, how much water will be released from a confined aquifer due to the elastic compression of the aquifer rocks and expansion of the water that caused by the decrease of pressure.

Groundwater storage is accumulated in a long-term dynamic process of the interaction of recharge, flow, and discharge. When the balance between recharge and discharge keeps relatively stable, storage is also stable. However, if the recharge varies periodically, for example, in a hydrological and meteorological cycle the change of the recharge may be aroused by the change of rainfall, the balance will be disturbed and the storage and discharge will be changed accordingly. When less recharge than expected occurs, part of the storage will be consumed to meet the needs of discharge. On the other hand, more recharge than needed will enhance storage. Generally, storage can be regarded as a buffer in the hydrological cycle to adjust the balance between recharge and discharge therefore has much significance in evaluating groundwater resources.

To calculate storage accurately, the geometry, volume, specific yield and storage coefficient of the aquifer are of foremost importance. Furthermore, the condition of groundwater recharge and discharge and their dynamic characteristics must be aware in that they have a close relationship with storage.

3) Groundwater discharge

Groundwater discharge is the groundwater that leaves the aquifer unit with the dimension of L^3/T. It includes natural discharge and exploitation. With regard to groundwater resource evaluation, sustainable yield has the specific importance.

Natural discharge is the groundwater that leaves the aquifer unit in a natural way before or after exploitation, such as the outflux on the lower boundary of the aquifer, the evaporation from the unconfined water surface, leakage to adjoining aquifer unit or layer, and etc. Evaporation and leakage may decrease with the decline of water level while the depression cone develops during exploitation and the lower hydraulic gradient may become gentler, or even reverse, resulting in the reduce of outflux. Therefore natural discharge after exploitation is usually less than that before exploitation.

Sustainable yield is defined as the amount of water in unit time that can be taken from the aquifer in a sustainable manner without producing an undesirable result. The terms of exploitable yield or safe yield are also widely adopted referring to the same concept. Sustainable yield cannot be simply taken as the water quantity that the aquifer is able to yield, neither the maximum capacity of the water-yielding construction, but can be considered as the upper limit of exploitation. A prevailing idea in the hydrogeology field throughout the world is that, sustainable yield can be determined by the long-term mean annual recharge (basin's natural baseflow), while the actually exploitable groundwater resources are governed by technical, environmental and legal requirements on the minimum baseflow and/or minimum groundwater level. From this point of view sustainable yield has a close relationship with the hydrodynamic balance accompanied by groundwater recharge and discharge. Generally, the un-compensable storage in aquifer should not be consumed by sustainable yield and if it happens, the used part of storage is required to be compensated in the next recharge period.

In recent years, there has been an emerging controversy on the determination of safe yield. As the representative of the adverse side, Bredehoeft (2002) points out that the idea that the recharge is important in determining the magnitude of sustainable development has no basis and is a myth. By quoting and analyzing some specific cases of developing aquifers, he stated that the important entity in determining the sustainable groundwater development is capture, which is closely related to the aquifer dynamics. Therefore hydrogeologists should be occupied in studying aquifer dynamics via groundwater model. Because Bredehoeft condemns the association of recharge and sustainable development so forcefully, Sophocleous and Devlin (2004) discuss the relationship between recharge and sustainable development in terms of "when and where". Though Bredehoeft gives detailed analysis to prove his point, the quoted cases are simple ones and can't stand for any complex groundwater system, or regional aquifer system. Since recharge is the source of groundwater, even the sustainable development is associated with aquifer dynamics, influence on ecological system, water-yielding construction, there is no way to separate it from recharge, especially for a regional groundwater study. In this study, the determination of sustainable yield of TMG aquifer system will be estimated on the basis of recharge, discharge and regional water budget.

From the aforementioned, recharge, storage and discharge are not isolated from each other, but can be inter-transmitted. Naturally, recharge occurs at the upper reaches of a hydrogeological unit, from where enters the aquifer, and then becomes storage. At the same time in the lower reaches some of the storage leaves the aquifer and becomes discharge. During the recharge period the recharged water is stored in the aquifer, and is going to be drained out of the aquifer as discharge after the recharge period. In the case of exploitation on a specific site, sustainable yield is composed of the storage in depression cone and the recharge to the depression cone, while the latter usually includes the additional recharge (induced recharge) and the reduced part of natural discharge. This type of groundwater resource classification is sketchily shown in Fig. 2-1.

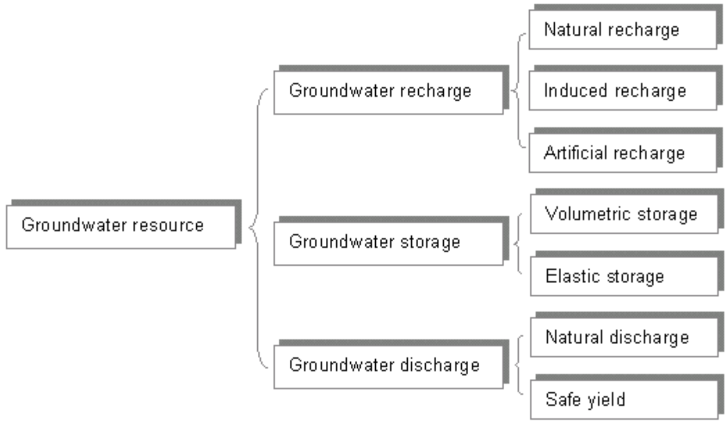


Fig. 2-1 Groundwater resource classification

2.2.3.2 The relationship between recharge, discharge and storage

Recharge vs. Sustainable yield

As discussed in the previous section, the sustainable yield of groundwater system is mainly dependent on recharge. In general the natural recharge is invariable before and after exploitation. It depends on the natural hydrogeological setting and is irrelative to water-yielding construction.

Induced recharge is aroused by the exploitation of the groundwater resource. Therefore part of the sustainable yield is closely related to induced recharge. The increase of exploitation will improve the induced recharge. Under the natural condition there is no induced recharge. Consequently, if there is the possibility to increase the induced recharge, the sustainable yield can probably be improved, or it is not necessary to expand the exploitation.

Theoretically, sustainable yield may equals to recharge (including natural recharge and induced recharge) while practically it is impossible because natural discharge occurs all the time, more or less, which definitely lead to the conclusion that sustainable yield should be less than recharge. The reliability of the water resource, the limitations of the exploration, and the imprecise calculation and assessment of the hydrogeological parameter are other factors that cause the sustainable yield to be less than recharge.

Recharge vs. storage

The natural recharge and induced recharge enters aquifer and becomes storage first, after which the storage is pumped out as yield during exploitation. Therefore the relationship between recharge and storage can be described as, storage comes from recharge and recharge is accessed through storage.

The thickness of aquifer is the most important parameter to the determination of storage, which can be expressed as:

$$Q = f(M) \tag{2-4}$$

Where Q denotes storage, M the thickness of aquifer, and f is the function that transmits the aquifer thickness to storage.

During the dry season when water requirement is higher than recharge, part of the storage must be depleted to compensate the shortage of recharge and keep the dynamic hydrological balance, which makes the storage serve as a buffer zone. In arid area, when the storage has been over exploited and the recharge period is short as well, the recovery time of the storage should be planned to be less than the recharge period, otherwise the dynamic balance of the exploited aquifer will be broken.

2.2.4 The components of sustainable yield and the method to expand exploitation

As aforementioned, both sustainable yield and natural discharge are on the side of discharge in a hydrological cycle of an aquifer. Sustainable yield is expected to increase by decreasing natural discharge. In the condition of exploitation, the following equilibration may exists in the aquifer at any time (Freeze and Cherry, 1979):

$$Q_E = Q_R - Q_D + \mu F \frac{\Delta h}{\Delta t} \tag{2-5}$$

Where Q_E is the exploitation quantity, Q_R the recharge quantity under the condition of pumping (including natural recharge and induced recharge), Q_D the natural discharge quantity, and $\mu F \frac{\Delta h}{\Delta t}$ the storage in the depression cone.

For the convenience of explaining the changes between before and after exploitation, the above formula may be rewritten to another form. Assume that the natural recharge is $Q_R{'}$ and natural discharge is $Q_D{'}$ before exploitation, the increment of recharge aroused by exploitation (induced recharge) is ΔQ_R, the decrement of discharge aroused by exploitation is ΔQ_D. Then the following equation can be arrived,

$$Q_R = Q_R{'} + \Delta Q_R \tag{2-6}$$

$$Q_D = Q_D{'} - \Delta Q_D \tag{2-7}$$

The following equation is derived by substitution,

$$Q_E = Q_R{'} - Q_D{'} + \Delta Q_R + \Delta Q_D + \mu F \frac{\Delta h}{\Delta t} \tag{2-8}$$

Considering that the dynamic balance has been formed during the long-term natural hydrological cycle, the approximation, $Q_R' \approx Q_D'$ can be made. There is,

$$Q_E = \Delta Q_R + \Delta Q_D + \mu F \frac{\Delta h}{\Delta t} \tag{2-9}$$

Equation (2-9) shows clearly that exploitation quantity is mainly composed of the increment of recharge, the decrement of natural discharge and the storage provided by depression cone. However such condition is not invariable. Under different hydrogeological conditions different cases may evolved during the development of exploitation.

Case 1. Unconfined aquifer with perennially recharge

In the zone of perennial river, alluvial fan and pluvial fan that perennially recharged by surface water or river bank, when long-term groundwater extraction carries out and the depression cone expands to such an extent that the increment of recharge and decrement of discharge is enough to balance the abstraction, the depression cone is not going to expand any more and the storage is not going to be consumed, the relatively steady state of exploitation is arrived. In the steady state the constitution of the exploitation is,

$$Q_E = \Delta Q_R + \Delta Q_D \tag{2-10}$$

Such water source can be regarded as stable water source.

Case 2. Seasonally recharged unconfined aquifer

With respect to intermittent river, semi-arid front zone of the mountain and the seasonally recharged unconfined plain aquifer, the constitution of the exploitation during the wet season and dry season is different. During the dry season, the recharge has little or no effect on the aquifer, consequently the depression cone expands and the storage is consumed, which can be expressed by Equation (2-11):

$$Q_E = \Delta Q_D + \mu F \frac{\Delta h}{\Delta t} \tag{2-11}$$

During the wet season when the recharge is plenty, the depression cone shrinks and the used storage is compensated and recovered, as illustrated by Equation (2-12):

$$Q_E = \Delta Q_R + \Delta Q_D - \mu F \frac{\Delta h}{\Delta t} \tag{2-12}$$

In such condition the storage is adjusted to ensure the exploitation in a relatively steady state, which is regarded as adjustable water source.

Case 3. Confined aquifer far from recharge zone or discharge zone

For the deep confined aquifer located in the extensive plain or the large-scale artesian basin, the increased recharge and decreased discharge resulted from exploitation can't meet the exploitation needs, consequently the elastic storage continues to be depleted and the depression cone expands persistently. The constitution of exploitation in such condition is,

$$Q_E = \Delta Q_R + \Delta Q_D + \mu F \frac{\Delta h}{\Delta t} \tag{2-13}$$

Equation (2-13) is similar to Equation (2-12) in the form whereas the previous two items in the right side is very limited and the third is dominated. In such water source, the elastic storage is depleted and the steady state will never be arrived, which can be regarded as depleted water source.

The abovementioned case 1, 2 and 3 are typical cases. Many transitional types also exist due to the complexity of the hydrogeological condition.

2.3 Determination of recharge and storage

2.3.1 Determination of recharge

Quantification of recharge is of uppermost importance in groundwater resource evaluation. However it is impossible to measure recharge directly at both catchment and regional scale. With the development of groundwater study and practical experience, a number of efforts have been made to the recharge estimation, from which three classes of methods are summarized as follows:

1) Recharge estimation using rainfall data

The surface soil layer is considered to have limited water-holding capacity. During the process of rainfall, when rainfall is plenty to compensate the water loss in soil by evaporation and saturate the soil layer with water, the gravitational water occurs in the soil layer and then gathers to produce the subsurface runoff. Furthermore, when rainfall intensity is larger than the infiltration rate of the gravitational water, surface runoff will also be produced. Water balance equation may be established to determine the subsurface runoff for every rainfall event. The disadvantages of this method are the determination of previous influential rainfall, evaporation and the infiltration rate of the surface runoff and the subsurface runoff.

2) Recharge estimation using hydrodynamic methods

This class of methods is based on water balance. The study area can be conceptualized as a groundwater reservoir with six open faces on the top, bottom, left, right, front and back. The influx quantity is considered on the surrounding four faces and can be calculated by Darcy Law, while on the top rainfall infiltration, river leakage, irrigation infiltration and etc. are considered and on the bottom, the leakage from other aquifer or aquitard is considered. The disadvantage is that a comprehensive reconnaissance on the geological and hydrogeological setting is required. An alternative method is calculating the total outflux of the groundwater reservoir.

3) Recharge estimation using hydrological analysis method

Based on the relationship of inter-conversion between precipitation, surface water and groundwater and the long-term hydrometeorological data, this method calculates the groundwater recharge on a statistical way. According to the actual condition this method can be classified into coefficient method, stream flow method, hydrological separation method, flux difference method, water balance method, and etc.

2.3.2 Determination of storage

In most publications, the calculation of groundwater storage is expressed as,

$W = \mu \cdot V$ (Unconfined aquifer) (2-14)

Where W is the groundwater storage quantity, μ the specific yield of the unconfined aquifer and V the volume of the unconfined aquifer.

$W = F \cdot S \cdot h$ (Confined aquifer) (2-15)

Where W is the groundwater elastic storage quantity, F the area of the confined aquifer, S the storage coefficient of the confined aquifer and h the pressure head of the confined aquifer.

The above calculation for groundwater storage has been widely acknowledged, while two problems do exist. First, how to differentiate between unconfined and confined aquifer? Some aquifer systems have the confined characteristics locally but belong to an unconfined aquifer system regionally. Second, it makes no sense if only the elastic storage of confined aquifer is calculated in that the elastic storage is the released water aroused by the compression of the rock mass and the expansion of water when the piezometric level in confined aquifer reduces. In unconfined aquifer the same condition exists. It's only because that the specific yield of the unconfined aquifer is several magnitudes larger than the storage coefficient of it, the latter is usually overlooked in actual calculation. The elastic storage is insignificant when pumping in unconfined aquifer. When the piezometric level is higher than the upper aquitard, the storage in confined aquifer is mainly composed of subsurface runoff and volumetric storage. When the piezometric level is lower than the upper aquitard, the confined condition no longer exists and the confined aquifer is similar to unconfined aquifer.

2.4 Determination of sustainable yield or exploitable groundwater resource

A lot of methods to determine sustainable yield have been accumulated during practical experience in groundwater resource utilization. Some of them are listed here (Manual, 1983).

2.4.1 Drainage compensation method

In the case of intermittent river and local karst zone, if natural recharge is taken as the only criterion of exploitation, the original exploitation plan probably can't be implemented. Because in such areas the natural recharge varies largely with season and even the recharge of the whole year is very limited in some cases. However the seasonal recharge potential may be utilized properly under the condition of exploitation in a drainage-compensation way. During dry season or low flow year part of storage can be extracted and the groundwater level will fall accordingly. In wet season or high flow year, the over-exploited storage could be compensated by recharge from plenty of rainwater and the groundwater level will rise. More recharge in wet season is needed than the natural recharge before exploitation to make up the large draw down caused by over exploitation during dry season. This method also requires that, the first, the drainable storage in dry season or low flow year be enough to satisfy the needs of continuous exploitation and, the second, the recharge available during the wet season or high flow year be enough to compensate all rather than part of the over used storage in dry season or low flow year.

2.4.2 Water balance method

Water balance method is a basic way to evaluate regional groundwater resource. The principle of water balance is that during the dynamic process of hydrological cycle, the difference between recharge and discharge equals the volume change of water in a specified aquifer at any time. On regional scale, the hydrogeological setting is usually complex and needs large amount of comprehensive reconnaissance, which makes it very difficult to employ other methods. The advantage of water balance method is that it is simple and easy to implement.

2.4.3 Pumping test method

Usually on a site scale before groundwater abstraction is made, pumping test should be done in the monitoring well in terms of the expected exploitation condition (designed draw down and designed yield). Usually the pumping test starts from the dry season and lasts one to several months. The dynamic changes can be monitored from the start to the recovery of water level. The observational data can be adopted to evaluate the exploitation resource. This method is fit for a small-scale water source with a complex hydrogeological setting that needs an imperative resource evaluation.

2.4.4 Lumped well method

Wells are usually irregular spaced especially where the water-bearing condition varies largely in the wide-span area. The mathematic problems will be possibly encountered when using groundwater dynamic method to evaluate the well yield. A lumped well may be a solution to such condition if not a precise evaluation is required. After the extraction from the irregularly distributed wells, a uniform depression cone is formed around the periphery of these wells, which can be assumed as an analog of a lumped well. The yield of the group of wells equals to the yield of the lumped well and the yield of each actual well can be deduced subsequently in general way.

2.4.5 Correlation analysis method

During groundwater dynamic process, most of the groundwater related physical quantities are not stable but vary with the process. Correlation analysis can be used to analyze the relationship between groundwater related variables and the influential factors, sort out the ranking of these influential factors according to their respective effect on groundwater, then forecast the dynamic trend of groundwater.

2.4.6 System theory method (Lumped parameter method)

System theory method comes from statistics technology and automation technology. A system is composed of a physical entity, input function and output function. The output function is derived by the interaction between the input function and the physical entity. Two processes are involved in the system theory, i.e. recognition and prediction. Recognition process deals with the determination of the parameters that describe the system. This could be achieved by analyzing the existing input and output. Prediction process is used to predict the output of the system from given input and the descriptive parameters derived from the recognition process. It requires that both the input function and the output function be single and the physical entity is temporally stable. In groundwater resource evaluation it is usually used to do stream flow prediction by setting rainfall as the input function, stream flow as the output function and the aquifer as physical entity.

2.4.7 Hydrograph separation method

It is commonly accepted that a river's hydrograph consists of baseflow (groundwater runoff), interflow and direct runoff. The hydrograph separation method is used to separate baseflow from a hydrograph by removing quick (or high) flow from slow (or low) flow. Usually a perennial river is recharged by rainfall-induced surface runoff (direct runoff) and groundwater. During the low flow season, the river flow is predominantly sustained by groundwater discharge. During high flow season, most of the river flow is largely recharged by direct runoff and very little by groundwater or the groundwater is recharged by river reversely. The groundwater runoff can be separated from a hydrograph with a comprehensive analysis of the hydrogeological setting. If the hydrograph separation is applied to each river in a groundwater catchment, the natural groundwater runoff can be estimated easily for the catchment. This method is applicable to non-karst zone where the interaction between surface water and groundwater is active, especially for the unconfined aquifer on alluvium.

2.4.8 Frequency analysis method

Groundwater resource is different from other mineral resources in that it fluctuates seasonally and receives recharge from rainfall. The long-term dynamics of groundwater and the interference among exploitation zones should be taken into account in the regional groundwater resource evaluation. The exploitable groundwater resource or sustainable yield should be a variable due to the movement of groundwater and the influence and restrict by nature or human being. Frequency analysis method is used to determine the reliability of exploitable groundwater resource by analyzing the quantity and frequency distribution of the groundwater recharge. It is applicable to the unconfined or confined aquifer on alluvial plain or flood plain.

2.4.9 Spring dynamic analysis method

Generally spring or spring clusters are the discharge points of the hydrogeological unit where they are located. A depression cone could be formed surrounding the cluster of springs, which can be regarded as abstraction wells working on the aquifer. The "pumping test" of large-scale cluster of springs is difficult to be done artificially with the large drawdown, long durative time and extensive influential zone. Therefore the natural dynamics of the cluster of springs is capable to expose the characteristics of groundwater occurrence and development. The natural depression cone reflects the main recharge source, direction and scope. Hence the monitoring data of the springs could be more representative and valuable than the artificial pumping test data.

2.4.10 Hydrogeological analog method

Some areas are well studied in terms of hydrogeology while others are not. Hydrogeological analog method is to adopt the hydrogeological parameters of a well-studied aquifer to calculate the yield of another aquifer that is hydrogeologically similar to the well-studied one. Considering that no aquifers are exactly the same, all the parameters adopted must be properly modified. Rainfall infiltration rate, hydraulic conductivity, specific yield, drawdown, and etc. are the most commonly used parameters when using hydrogeological analog method.

2.4.11 Electric analog method

The basic law, or the partial differential equation of the groundwater flow in aquifer is similar to that of the electricity flow through conductor, which is the principle of electric analog method. There are two basic categories of electric analog models. Continuous systems are those in which aquifer properties are modeled by an electric conductive medium that is continuous in space. In this category the conductive liquid or solid is modeled as the analogous aquifer. The other category mainly represents discrete systems in which aquifer properties are simulated by an assemblage of discrete electric elements forming a network. Resistance-capacitance and resistance networks belong to this group.

2.4.12 Numerical method

Due to the complexity of the mathematical model of groundwater flow, the irregular shape of study area and the anisotropy and heterogeneity of the aquifers, it is usually difficult to get the analytical solution of the mathematical model. Numerical method is usually employed to achieve an approximate solution by discretizing the area into small anisotropic and homogeneous sub areas or grids. Numerical method are grouped into finite-difference method (FDM), finite-element method (FEM), boundary-element method (BEM) and etc. With the fast growing of programming techniques and computer capacities, numerical method has been extensively used in groundwater study. However, the basis of numerical method is analytical method and the precision of the simulation is dependant on the applicability of mathematical model and model parameters. If the mathematical model is not fit for the real condition, or large errors are introduced by parameters input, both the input and the output could be rubbish.

2.5 Summary

Groundwater resource cannot be regarded as equivalent to groundwater. Three conditions must be met to make the groundwater as resources, including: 1) the existence of water bearing space, namely aquifer, 2) the recharge condition, and 3) technical feasibility of groundwater extraction.

By considering the dynamic nature of the groundwater resource, it may be classified into recharge, storage and discharge. The three of them are interrelated to each other in the hydrological cycle. Sustainable yield is the most concerned part of groundwater discharge under exploitation condition, which could be expanded in various hydrogeological conditions.

Recharge, storage and discharge can be estimated both locally and regionally using different methods depending on the availability of data.

3. Geological and hydrogeological backgrounds of Table Mountain Group

3.1 Introduction

Currently, groundwater development in South Africa is mainly concentrated on fractured rock aquifers in which there are three major aquifer systems consisting of dolomite, dolerite dikes and TMG sandstones. The TMG extends from Western Cape to Eastern Cape in South Africa (Fig.3-1), comprising a thick sequence of hard sedimentary rocks dominated by fractured sandstones with a thickness ranging from 900 m to 5000 m. With the results from a lot of groundwater practice in the TMG aquifers, together with the cognitions on lithological characteristics, stratigraphic buildups and regional structure of the Table Mountain Group, it seemed to be concluded that the TMG is a regional aquifer system that extends to big depth (Issar, 1995) and there accordingly is a huge groundwater reservoir underneath the area. It is also acknowledged that the aquifer systems are mainly consisted of sandstones, siltstones, interbedded by shales and mudstones. As underlain by Precambrian metamorphic rocks and overlain by mid - to neopaleozoic basin deposits, and bounded by some regional faults such as Kango and Worcester faults, the TMG aquifer systems has the potential for bulk water supply in the Western and Eastern Cape provinces. As the important basis of hydrogeological settings, aquifer properties, groundwater storage, and circulation, it is necessary to understand the geological and hydrogeological backgrounds of TMG as discussed in this chapter.

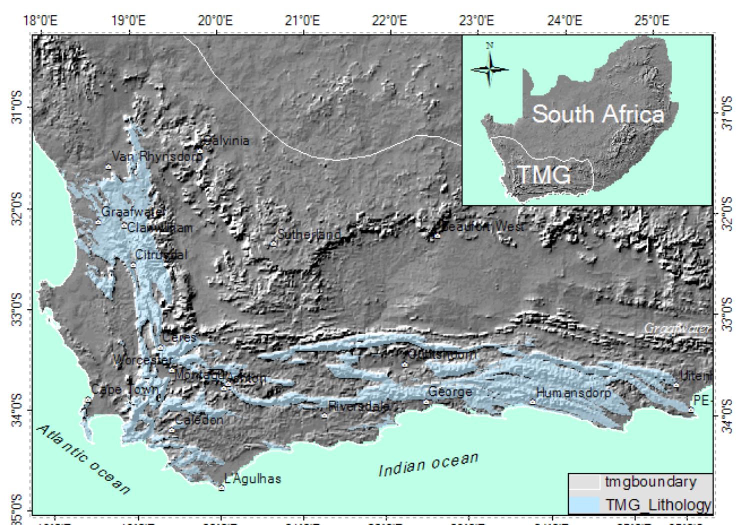


Fig. 3-1 Spatial distribution of TMG aquifer system

3.2 Geology of Table Mountain Group

3.2.1 Geomorphology

The TMG extends to an area of about 248400 km^2 with 37000-km^2 outcrops that constitute high mountain terrains in the Western and Eastern Cape provinces. On a regional scale it covers mountains, wave-cut plains and intermontane drainage basins, which form the principal geomorphologic types in this area. The modern landform patterns of the TMG are of main results from quaternary processes including crust heaves, physical and chemical erosions, which lead to the rolling landscapes with a relative relief of 200~1700m. The mountain peak can reach 1900~2250m in Hex River Mountain and 1500~2000m along Langeberg and 1700~2000m on Swartberg Mountains. Comparing with overlaying argillaceous rock formations and underlaying metamorphic rocks, geomorphologic patterns of TMG are also characterized by the highly stick-out mountains and steep slopes with quite thin or even no soil covers over its outcrops. Most of mountains form the backbones of the TMG geomorphologies that are firmly controlled by the structure and lithologies. Among them, from west to east, is Bokkeveldberg - Cedarberg - Skurweberg and Hex river mountains, turning eastward to Langeberg - Outeniekwaberg Mountains. To the north there are Witteberg-Swartberg- Baviaanskloof Mountains. In betweens are intermontane basins and flood plains, most of which are covered by weathered mantles from argillaceous rocks and fluvial deposits.

3.2.2 Stratigraphy

The entire stratigraphic succession in the TMG area includes the basement (Precambrian), Cape Supergroup (Ordovician ~ Devonian) and part of Karoo Supergroup (Permian ~ Cretaceous). The succession with their associated thickness and lithological compositions were summarized in Table 3-1, in which the TMG of Cape Supergroup has most of significance associated with the occurrence of groundwater in both quantity and quality in the area. Underlain by Precambrian basement rocks and overlain by mid - to neopaleozoic basin deposits, the TMG is composed of a continuous sequence of quartz arenites with minor shale layers. According to Rust (1967), Rust (1973), Joneson (1991), Broquet (1992), and Thamm (1993) the formations of the TMG are described as the following:

1) Piekenierskloof Formation The lowermost unit of the TMG consists of conglomerate, quartz arenite and minor mudstones, which is confined to the West Coast. Reported maximum

thicknesses for the Piekenierskloof Formation vary between 900m northwest of Citrusdal and 390m at Piketberg.

2) The Graafwater Formation is characterized by purple, thin-bedded, ripple-marked and mudcracked sandstone, siltstone and shale beds. Recorded maximum thickness of this Formation is 424m in the type area west of Clanwilliam.

3) The Peninsula Formation comprises a sequence of coarse-grained, white quartz arenite with scattered small pebbles and discrete thin beds of a matrix-supported conglomerate. The Formation reaches a thickness of about 1800m at Clanwilliam in the west, but is reportedly much thicker in the Eastern Cape.

4) The Pakhuis Formation comprises about 40~80-m glacially derived sediments, but is restricted to the southwestern Cape.

5) The Cedarberg Formation interrupts the monotonous arenitic character of the TMG with a thickness of 50-120m shale, siltstone and silty sandstone. It has much significance in hydrogeological sense.

6) The Nardouw Subgroup, with its three subdivisions, the Goudini, Skurweberg and Rietvlei Formations, is another thick (maximum 1200m) unit of sandstone that varies between quartz arenite, silty and feldspathic arenites, accompanied by some very minor interbedded conglomerates and shales. This lithological diversity, together with textual, grain size and bedding thickness differences, lead to pronounced differences in weathering, structural and hydrogeological characteristics. The basal unit, the Goudini Formation, is characterized by reddish weathering, thin sandstone beds with common shale intercalations. The Skurweberg Formation principally consists of thick-bedded arenites. Topmost unit of the Nardouw Subgroup, the Rietvlei Formation contains more feldspar and is characterized in the field by thicker vegetation growing on it. The contact with the overlying dark shale of the Bokkveld Group is usually abrupt.

3.2.3 Structure

Tectonically, the TMG region has been identified to be a part of African Craton. Structures in the TMG were produced by the development of the Cape Fold Belt (CFB) during the Permo-Triassic Cape Orogeny (De Beer, 2001) extending from Australia through Antarctica and South Africa to South America (McCathy and Rubidge, 2005). Further tectonic modification of the area occurred during the fragmentation of southwestern Gondwanaland during the late Mesozoic, disrupting previous topographies with a series of tensile and dextral displacements.

Table 3-1 Geological succession of the Cape Supergroup

Supergroup	Group	Subgroup	Formation	Thickness (m)	Lithology
Karoo				7000	Basin sedimentary sequence during the Permian ~ Cretaceous
Cape	Witteberg	Lake Mentz	Waaipoort	340	Shale, siltstone, thin sandstone
			Floriskraal	80	Sandstone, siltstone, shale and grit
			Kweekvlei	200	Shale
			Witpoort	850	Quartzitic sandstone, minor siltstone
		Weltevrede	Swartruggens	300	Siltstone, mudstone and thin-bedded sandstone
			Blinkberg	15-90	Thick-bedded quartzitic sandstone
			Wagendrift	135-165	Siltstone, sandy shale, mudstone and lithic sandstone
	Bokkeveld	Traka	Karoopoort	40	Siltstone, sandy shale and minor mudstone
			Bidohn/Adolphspoort	1000?	Siltstone, shale, sandstone
			Klipbokkop/Karies	1200	Shale
			Wuppertal	26	Sandstone, siltstone
		Bidouw	Waboomberg	200	Siltstone, shale
		Ceres	Boplaas	100	Sandstone
			Tra – Tra	350	Shale, siltstone
			Hex River	70	Sandstone, siltstone
			Voorstehoek/wartkrans	300	Shale, siltstone
			Gamka	200	Sandstone, siltstone
			Gydo	600	Shale, siltstone
	Table Mountain	Nardouw	Rietvlei/Baviaa-nskloof	300	Feldspathic quartz arenite
			Skurneberg/Kouga	500	Quartz arenite
			Goudini/Tchando	400	Brown-weathering arenite, minor siltstone, shale
			Cedarberg	50~150	Silty shales and shaly siltstone
		Peninsula	Parkhuis	70	Fluvio-glacial, tillite folded, diamicite, quartz arenite and thin-bedded quartzitic sandstone
			Penninsula	1500	Largely thick-bedded, coarse-grained quartz arenite
			Graafwater	25-65	Thin-bedded sandstone, siltstone, shale and mudstone
			Piekenierskloof	10-150	Quartzitic sandstone with coarse-grained to gritty zones and rudites
Basement			A suite of moderately to lightly metamorphic Precambrian sedimentary rocks. And cape granite suite.		

The presently exposed structure and thickness of the TMG rocks are the result of initial deposition within an east-trending basin or trough (Rust 1973) along the southern and southwestern Cape regions. The CFB is traditionally divided into two branches, namely the western and southern branches, and in between is the structural syntaxis (Fig.3-2), of which the structural backbone extending from the northwest to the south near Cape Peninsula and incurve to the east near PE. The exposed width of the western branch is about 150 km, and the southern branch is about 200 km. Both branches are arcuate in plan view and concave towards the Karoo Basin, converging with northeast-trending folds in the structural syntaxis of the southwestern Cape.

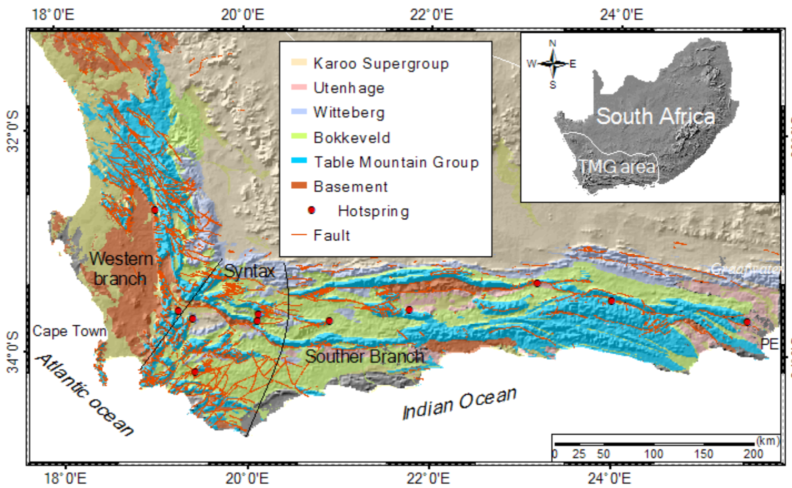


Fig.3-2 Map of simplified geological structure of the TMG, where the backbone of the CFB extending from the northwest to the south and incurving to the east (PE).

Table 3-2 Regional structural domains in the Cape Fold Belt within the TMG area

Domain	Folds	Shortening %	Pelite Cleavage	Metamorphism	Faults
1	No discernible folding	Very low	None	Diagenetic	None
2	NW-SE, Zonal development, kinks, λ =40km, open folding	Variable, <15%	None	Lowest grades	Major NW-SE, shorter E-W and minor NE-SW faults
3	Major N-S and NE-SW folds, minor NW-SE, interference, λ=20km, open to tight folding, no overturning	Low, <25%	Weak to non-existent, but strongly fractured	Lowest grades, little neoformed micas	WNW-ESE, slightly less major faults than Domain 1
4	E-W, local northwards overturning, minor NE-SW	>35%	Well-developed, axial planar	Low grade, abundant neoformed mica	WNW-ESE and WSW-ENE
5	NW-SE and NE-SW, open folding, no overturning	<25%	Weak to non-existent	Lowest grades, little neoformed mica	Major NE-SW, lesser NW-SE
6	NE-SW and E-W folding, some overturning	>35%	Strongly developed, axial planar	Low grade, abundant neoformed mica	NE-SW and E-W
7	E-W, overturning common	>35%, thrusting	Strongly developed, often crenulations	Low grade	Curved thrusts, E-W normal faults
8	E-W, locally overturned	40-30%	Well-developed, axial planar	Low grade	E-W major faulsts
9	E-W, mostly overturned	70-40%	Well-developed, axial planar, crenulated	Low grade, quartz recrystallized, phyllites common	E-W major faulsts, thrusts

Based on the folding and fracturing characteristics, The TMG area within CFB was further subdivided into 9 structural domains by De Beer (2002, cited by Fortuin, 2004). The structural character of each domain has been summarized in Table 3.2.

The ability of the TMG rocks to contain water is determined by the amount and properties of fractures that are regarded ad secondary porosity. As most of these rocks are remarkably densely packed with intense secondary overgrowths of quartz within the arenites, such porosity can only be created through deformation and faulting during various tectonic movements in the geological history. Cleavage can enhance porosity, but is not indispensable (Fortuin, 2004).

3.3 Hydrogeological backgrounds of Table Mountain Group

As underlain by Precambrian metamorphic rocks, overlain by mid- to neopaleozoic basin deposits and bounded by some regional faults such as Kango and Worcester faults, the southmost aquifer system in African continent has the potential to become a major source of bulk water supply for both agricultural and urban requirements in the Western and Eastern Cape provinces of South Africa. Extensive exploration and exploitation of the groundwater resource in the aquifer system have been done for about 30 years. Prior to the early of 1990s, the main groundwater practices of wellfields developed in the Table Mountain Group aquifers were restricted to Hex, Ceres, Breede, and Agter Witzenberg Valleys and small-scale municipal use by small towns along the coastal and inland outcrop areas. The more recently important developments of explorations and exploitations at TMG wellfields are Klein Karoo Rural Water Supply Scheme started in 1987, Boschkloof near Citrusdal in 1997/98, Hermanus in 2001/02, Koo Valley in 2002/03, and the Cape Municipality groundwater development being under way. So far there are More than 45 Mm^3 of groundwater is annually abstracted in about 30 locations for the requirements of municipalities, irrigation farmers and holiday resorts. Minor users are the smaller scale farmers, homesteads and stock farms. The main gaps in development are in the northern and eastern extremities and in the mountainous inland area of the Eastern Cape. Currently, major problems faced are the lack of information on the properties of the huge fractured rock aquifers and shallow and deep groundwater circulation. The establishment of groundwater units may help to present and analyze the properties of aquifer system and boundary conditions for the TMG aquifer system in the huge study area. Each unit has relatively independent properties of groundwater storage and circulation, which is different from the others.

3.3.1 Previous hydrogeological division

Based on the type of openings – primary or secondary – lithostratigraphy, physiography and climate, Vegter (2001) divided South Africa into 64 groundwater regions, in which 23 regions are located within the TMG deposit area. In his delineation, TMG is not much more hydrogeologically significant compared with the adjacent Bokkeveld Group and Witteberg Group.

Another division is based on different thickness of geological successions or their positions in the CFB and on associated tectonic regimes. The TMG aquifer system was divided into five sections (Fortuin, 2004), namely:

1) Western Area, i.e. CAGE-type;

2) Central Area, i.e. Agter Witzenberg – Ceres – Hex - Koo Valley and Villiersdorp;

3) Coastal Belt, i.e. from Kleinmond to Mossel Bay;

4) Klein Karoo;

5) Eastern Cape, Plettenberg Bay to Prot Elizabeth.

Extensive hydrogeological studies have been carried out in areas A, B and D, but less in areas C and E.

3.3.2 Hydrogeomorphology

The influences of features/patterns on groundwater behaviors in the TMG areas have been limitedly delineated. 11 primary catchments involved are Berg, Olifant-Doring, Bree, Salt, Sounrits, Gamtoos and Sundays rivers including 551 quaternary catchments that control not only the local base level of corrasion but water drainage systems as well. The rivers cutting through various formations of the TMG and structural units of the area produce diverse watercourses and slope systems, which lead to both the TMG rough and cragged surface and different relief mountain and hill systems. These definitely influence the groundwater systems in terms of recharge locations, interflow behaviors, and corresponding groundwater circulations.

3.3.3 Hydrostratigraphy

TMG aquifer system is constituted by Nardouw Subgroup (Nardouw Aquifer), Peninsula Formation (Peninsula Aquifer) as the main aquifer and the interbedded Cedarberg Formation has been identified as aquitard between the two main aquifers. Each of the three units has unique hydrogeological characteristics, based on its associated lithology, fracturing styles, proximity to recharge areas, etc. All these influence the water bearing capacity, groundwater quality and yield of a particular unit.

The Peninsula Formation consists of pure quartz arenites with a very low primary porosity due to the cementation of individual sand grains. Porosity has been further reduced by low-grade metamorphism associated with the Cape Orogeny. However, increased rock induration led to a higher potential for brittle fracturing during deformation, as well as higher fracture frequencies and thus a well-developed secondary porosity, which serve as the main groundwater storage space and flow path. The Peninsula Aquifer usually outcrops at higher altitudes and is separated from the Nardouw by the Cedarberg Formation, which are TMG window areas. They receive more recharge due to the topography. Groundwater flow paths and residence times are shorter, providing low EC/TDS groundwater (Rosewarne, 2002)

The Nardouw Subgroup contains more silty or shaly interbeds and associated higher feldspar content compared with Peninsula Fomation. Shale layers have a great impact on the fracturing and folding style of TMG aquifers, which give rise to large variations in hydraulic conductivity. In general, an increase in shale layers leads to ductile deformation (folding) as opposed to brittle deformation (more fracture) with less shale layers. Clay resulting from the chemical weathering of feldspar can clog the secondary groundwater flow paths (fractures) and reduce permeability further.

The Cedarberg Formation is an aquitard, which may contain water, but does not transmit large amounts, unless transected by a fault. It serves as a confining stratum overlying on Peninsula Formation and can probably leads to significant blow-out yield of the underlying Peninsula Formation if thoroughly drilled. The barrier nature of the Cedarberg Formation also can be seen in the numerous spring occurrences at the Cedarberg/Nardouw and Cedarberg/Peninsula boundary in the Western Cape.

3.3.4 Springs

A lot of springs with different discharge rates occur in TMG area, which have been summarized by Meyer (2002) into three commonly occurred types:

Type 1: Shallow circulating springs

Shallow circulating springs are intermittent springs issuing from a network of joints, small fractures, contact zones of weathered mantle and bedrocks. They are seasonally controlled and cease to exist with the onset of dry weather conditions.

Type2: Lithology controlled spring

There are three sub-types in this type, springs issuing from contacts with interbeds (Cedarberg Formation), springs on the TMG/Bokkeveld Group contact and springs issuing from unconformities. The yields of lithology-controlled springs fluctuate in a wide range, maybe 10 times in some cases. Another characteristic of these springs is the excellent groundwater quality.

Type3: Fault controlled spring

There are eleven well-known hot springs occur in TMG area, which indicates the independent deep groundwater flow systems exist in the TMG terrestrial area. Among them the hottest spring is Brandvlei that implies a possible circulation depth of 1800~2000 m. These springs are interestingly distributed along the Cape Fold Belt (Fig.3-2) and have large constant flow rates. Five of the eleven hot springs are located in the syntaxis zone, which may indicate more frequently deep fracturing in that zone.

3.4 Summary

In order to study the groundwater resources in the area, it is very necessary to realize the complexity of lithology, structure, and geomorphology and to understand the hydrogeological setting of the aquifer system, based on the previous studies.

The TMG extends from Western Cape to Eastern Cape in South Africa, comprising a thick sequence of hard sedimentary rocks dominated by fractured sandstones. It seems to be a regional aquifer system that extends to big depth and there accordingly is a huge groundwater reservoir underneath the area. This aquifer system is mainly consisted of sandstones, siltstones, interbedded by shales and mudstones with a sedimentary sequence from the basal Piekenierskloof Formation to the top Rietvlei/Baviaanskloof Formation.

The hydrogeological setting of the TMG aquifers is extremely complex. Base on the lithology and the fabric and associated permeability of the rock materials, the aquifers can be mainly classified into Peninsula Aquifer and Nardouw Aquifer, in between is the Cedarberg Aquitard (shale), with the minor Piekenierskloof Aquifer restricted to the western coast area. According to aquifer thickness and the geographical location, The TMG aquifer system has been divided into five sections which are partially consistent with the division of national groundwater regions.

Groundwater explorations and exploitations in the TMG area have be unevenly conducted and mostly concentrated on the western portions and some parts along coastline mainly because of the uneven distribution and demand of the water sources.

4. Regional groundwater resource evaluation in TMG

4.1 Introduction

The utilization of surface water resources in the existing dams has reached the limits in the TMG area and the construction of new large dams may result in serious environmental problems in that most of the mountain areas along Cape Fold Belt belong to a diverse but threatened floral kingdom and ecologically sensitive (Hartnady and Hay, 2002). Also, it has been suggested that the TMG aquifer has the potential to become the major sources of bulk water supply to meet the requirement of irrigation, municipal city and holiday resort in the Western and Eastern Cape provinces, which is confirmed by the occurrence of the deep-seated hotsprings. However the shortage of proper resource estimations and the practical difficulties to this highly fractured rock aquifer system definitely impedes the optimal exploration and exploitation of the aquifers. The existing estimates of TMG groundwater resource potential have been reviewed in Chapter 1, most of which were roughly determined. It is extremely difficult to characterize the fractured rock aquifers due to the complexity of geometric and hydraulic properties of the aquifer system. It is also very challenging to transfer the knowledge gained from case studies at local level to regional understanding the present research is aimed at. At times a wrong estimation of the aquifer parameters would lead to the failure of a water supply scheme, as reported by Jolly (2002). As a major exploitation target, the TMG aquifers are expected to fill the wide gap between the increasing water demand and the limited existing surface water resources in a sustainable manner. Therefore the regional evaluation of TMG groundwater resources is of foremost importance in the context of integrated water resources utilization and management. The quantitative estimations of TMG groundwater recharge, storage and discharge are presented in this chapter based on the data processing and analyses largely carried out on GIS platform on a regional scale, from which the sustainable yield of TMG aquifer is recommended.

4.2 Data availability

All climate data are obtained from WR90, which was the project entitled "Surface Water Resources of South Africa 1990" funded by the South Africa Water Research Commission in March 1990 (Midgley et al., 1994). The project started in January 1990 and ended in 1994, and it yielded a wealth of information on surface water resource, including precipitation, evaporation, stream flow, land cover, water use and hydrological analysis, which is either adopted or adapted in this study. Borehole data are largely extracted from NGDB (National Groundwater Database), including elevation, simple geologic borehole logging, hydrogeological parameters estimation (which are very few), water level and pumping test data. References related to the TMG studies since 1935 have been critically reviewed and the data are captured.

4.2.1 The study area

TMG outcrop area is estimated at 37,000 km^2. The study area is traditionally limited to the areas of 80,000 km^2 along the Cape Fold Belt (Fortuin, 2004). However, the TMG is extended to a large extent dipping underneath the Karoo basin in the north, as will be illustrated in later section of this chapter. To study TMG aquifers properly as a unique groundwater circulation system independent from other systems such as Bokkeveld Group and Karoo Super Group, it is absolutely necessary to expand the study area to include not only the outcrop but also the area where TMG is underlain. The area is bounded by the zero-thickness deposit of TMG in the north and coastlines in the west, south, and east. The study area of 248,400 km^2 is demarcated using GIS techniques. TMG outcrop area accounts for 14.91% of the whole study area. Most of the TMG stratum expose on the mountainous areas along incurved Cape Fold Belt from Vanrhynsdorp in the northwest to Wellington/Worcester in the south then to Port Elizabeth in the east (Fig. 3-2).

4.2.2 Topographic data

Topographic data include the point elevation data and contours as shape files. The DEMs of the study area are constructed from these data using TopoGrid function on the platform of ArcInfo workstation (ESRI, 1996). The elevation for the study area ranges from 0 m to 2200 m and most of the TMG exposes in the mountainous area at the altitude of >1000m.

4.2.3 Geologic Data

The lithostratigraphic and structural information of the study area is mainly extracted from the digital geology map available from WR90 database and calibrated with the geological map sheets (1/250,000). Both the printed maps and the digital map provide abundant data for the studies of cross sections and further generation of isopach and isobath maps of TMG, which is essential for storage calculation.

4.2.4 Climatic and hydrologic data

Climatic and hydrologic data includes precipitation, streamflow, water-holding capacity and evapotranspiration data, which is used in the groundwater recharge and discharge estimation. It is well accepted that the recharge of TMG aquifers mainly takes place in the outcrop areas (Wu, 2005). These data are preprocessed accordingly using the Clip function in GIS.

4.2.4.1 Precipitation

Precipitation data from 1920 to 1989 are given in two forms, monthly average percentage of each hydro-zone and monthly observation data on rainfall stations. To make sure the study is on a mean annual basis, it is preferable to use the monthly average percentage data together with the isolines of mean annual precipitation (MAP) to obtain the monthly precipitation data of study area.

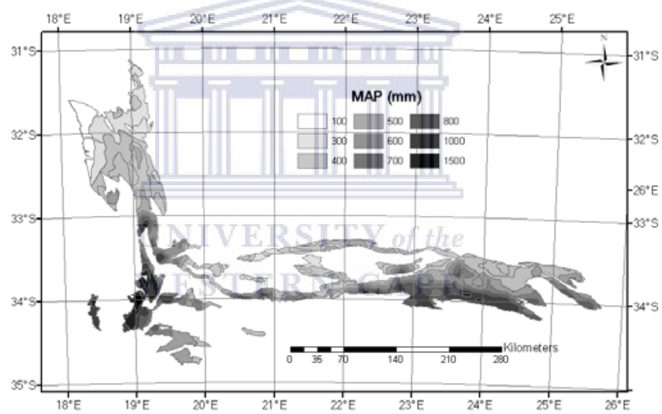


Fig. 4-1 MAP of TMG outcrop areas

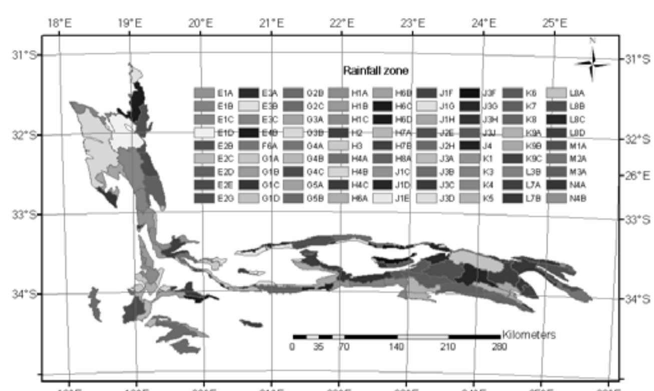


Fig. 4-2 Rainfall zones of TMG outcrop areas

Table 4-1 Monthly percentage for rainfall zones in TMG outcrop area (%)

Rainfall zone	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
E1C	5.64	4.03	2.74	1.77	2.45	3.21	8.05	13.80	19.09	15.30	15.59	8.34
E1D	5.05	4.17	2.91	1.72	2.37	3.58	8.06	13.64	20.58	15.18	15.03	7.72
G1A	6.14	4.16	2.93	2.58	2.64	3.29	8.00	14.35	17.42	15.27	14.33	8.90
G4C	7.38	4.82	3.27	3.44	3.63	4.11	7.87	12.59	15.77	14.20	13.77	9.18
H2	6.60	5.43	3.21	3.11	4.15	4.66	8.20	11.94	17.34	13.70	14.04	7.64
H4C	8.09	7.87	4.24	4.58	5.76	6.90	10.34	10.06	11.11	10.09	12.59	8.38
H6A	6.37	5.10	2.59	2.47	2.63	3.37	7.12	12.87	17.22	15.55	15.69	9.02
H8A	9.67	9.74	6.08	7.02	8.10	9.90	9.58	8.11	6.67	7.30	9.51	8.31
J1D	6.90	7.81	5.47	5.44	6.60	8.57	10.21	10.43	11.75	9.62	10.36	6.84
J3F	8.30	9.76	6.77	6.21	8.61	9.97	9.88	8.98	7.28	7.80	8.58	7.86
K1	9.62	9.82	6.50	7.49	7.79	10.25	9.15	8.04	6.66	7.05	9.01	8.61
K3	9.64	9.94	8.49	8.88	8.76	10.76	8.11	7.10	5.33	6.11	8.03	8.85
K9B	9.76	9.48	6.71	6.96	6.72	9.47	7.78	9.02	7.14	8.42	9.27	9.26
L8D	9.27	9.01	7.12	6.98	8.08	10.78	7.75	8.95	6.51	7.66	8.63	9.25
M1A	10.49	10.79	7.63	7.30	8.27	11.23	8.81	7.21	5.49	6.63	7.11	9.03

The MAP in TMG outcrop areas ranges from 100mm to 1500mm, as showed in Fig. 4-1. The 81 rainfall zones are identified in TMG outcrop areas (Fig. 4-2), which means that 81 rainfall patterns with different monthly percentage of MAP appear in the area. The monthly percentages of some rainfall zones are listed in Table 4-1. The resultant spatial distribution of monthly precipitation for the outcrop area can be derived by intersecting the two maps in GIS.

4.2.4.2 Streamflow data

Streamflow data throughout the country are available in WR90 (Midgley et al., 1994) and have been preprocessed for more reliable analysis. The distribution of Mean Annual Riverflow (MAR) in TMG outcrop areas is showed in Fig. 4-3. This dataset is also stored in two forms, monthly flow on gauge station and naturalized monthly streamflow in the quaternary catchments. Due to the same reason the latter is selected in the study. Based on the concept that streamflow is composed of baseflow and surface runoff, a digital recursive filter method is applied to separate them from each other, which will be expatiated in Chapter 5.

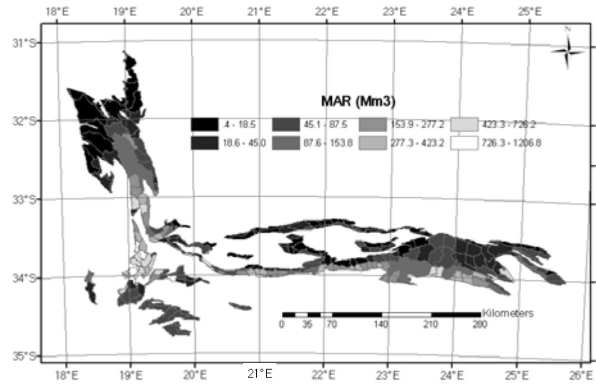


Fig. 4-3 MAR of TMG outcrop areas

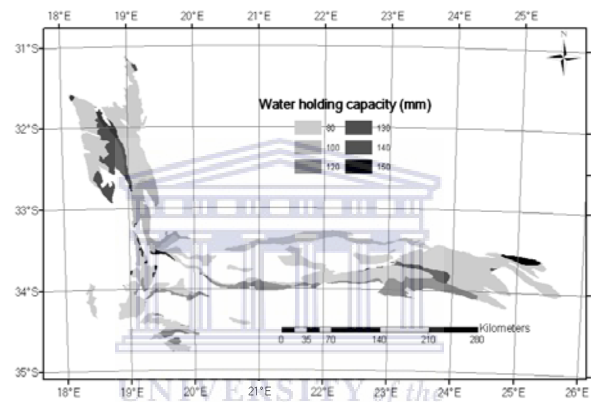


Fig. 4-4 Water holding capacity of TMG outcrop areas

Table 4-2 Typical Values for Soil-water Parameters by Texture (Unit: m)
(after ASCE, 1990)

Texture Class	Field Capacity	Wilting Point	Available Capacity
Sand	0.12	0.04	0.08
Loamy Sand	0.14	0.06	0.08
Sandy Loam	0.23	0.10	0.13
Loam	0.26	0.12	0.14
Silt Loam	0.30	0.15	0.15
Silt	0.32	0.15	0.17
Silty Clay Loam	0.34	0.19	0.15
Silty Clay	0.36	0.21	0.15
Clay	0.36	0.21	0.15

4.2.4.3 Water-holding capacity data

Water-holding capacity data is usually required in soil water balance calculation, as will be discussed later in this chapter. Global estimates of "plant-extractable water capacity" are available on a 0.5°grid (Dunne and Willmott, 1996). One reason for developing this global database was to eliminate the need for assuming spatially invariant plant-extractable water capacity in soil-water balance computations made over large areas. Information about sand, clay, organic content, plant rooting depth, and horizon thickness are used to estimate the plant-extractable water capacity. Table 4-2 gives some typical values of available water-holding capacity for the most common texture classes. In the current study, we take the global estimates as a reference due to the low precision of 0.5°grid and the irregular shape of study area. The soil map is provided by WR90 showing 82 soil types throughout the country. The soil types were analyzed in terms of features that are most likely to influence hydrological response, viz depth of soil, soil texture, and slope. In TMG outcrop area 18 soil types are included (Fig. 4-4). The water-holding capacity data for study area is derived from the combined analysis of the local soil map and global soil map.

4.2.4.4 Evapotranspiration

Evapotranspiration is the largest proportion in water balance estimation (Connelly et al., 1989). Although it includes soil evaporation and plant transpiration, a common function is applied to calculate the combination of the two components.

Pan Evaporation (ET) data in WR90 is interpolated for each location based on data from major regional centers. It is given in the same form as precipitation data and the same approach is adopted to derive the monthly pan-evaporation data as a percentage of MAE for each evaporation zone (listed in Table 4-3), from which the mean monthly evaporation can be determined and used for estimates of potential evaporation in the soil-water balance calculations. The distribution of MAE, the evaporation zones and the vegetation types in TMG outcrop areas are showed in Fig. 4-5, Fig. 4-6 and Fig. 4-7 respectively.

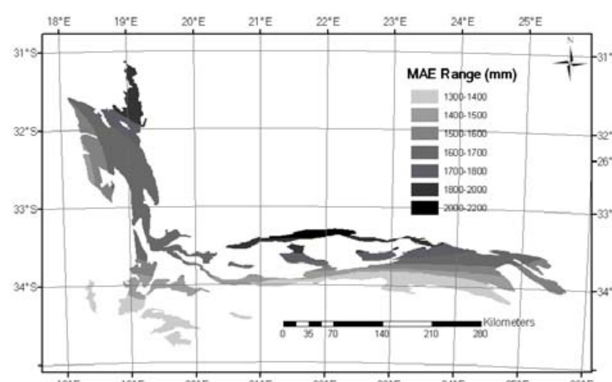


Fig. 4-5 MAE of TMG outcrop areas

Potential evapotranspiration (PET) is defined as the total of moisture evaporated from the soil surface and transpired by the plant roots when there is an unlimited water supply. Factors such as temperature, sunlight hours, wind, humidity and atmospheric pressure and the vegetation type affect the potential evapotranspiration. The simplest way to estimate PET is:

$$PET = ET * Pan\ Factor * Crop\ factor \qquad (4\text{-}1)$$

Where *Pan factor* is the ratio of open water evaporation or catchment transpiration to Pan Evaporation. Pan factors vary with location and season. *Crop factor* is the coefficient expressing the proportion of open water evaporation transpired by a crop under the same energy gradient, varying with stage of growth, plant type, plant density, sunlight, wind and soil conditions (Patterson, 2002). The Pan factors (Table 4-4) and Crop factors (Table 4-5) for each vegetation type in study area are listed as below (Midgley et al., 1994).

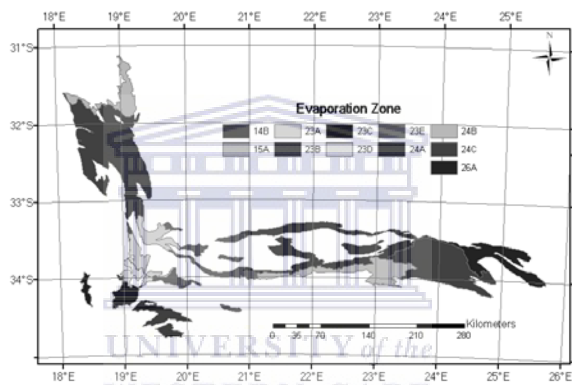


Fig. 4-6 Evaporation Zones of TMG outcrop areas

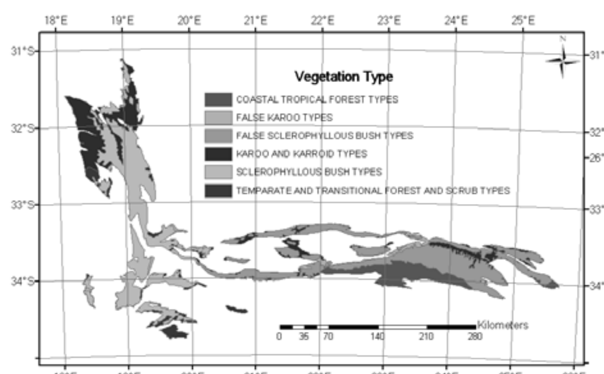


Fig. 4-7 Vegetation type of TMG outcrop areas

Table 4-3 Monthly percentage of evaporation zone in TMG outcrop area (%)

Evaporation zone	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
14B	9.58	11.40	12.32	12.64	10.23	9.57	6.92	5.41	4.76	4.52	5.53	7.12
15A	9.21	11.38	13.37	14.22	11.48	10.38	6.69	4.63	3.47	3.62	4.77	6.78
23A	9.19	11.46	14.11	14.78	12.40	11.16	7.05	4.34	2.94	2.96	3.83	5.78
23B	8.67	12.08	14.83	15.09	12.45	11.51	7.06	4.00	2.62	2.55	3.57	5.57
23C	8.76	12.23	14.38	14.73	12.43	10.86	6.76	3.90	3.00	3.32	3.90	5.73
23D	8.77	12.40	15.47	16.12	13.44	11.29	6.12	3.24	2.40	2.21	3.24	5.30
23E	9.65	12.36	14.97	14.98	11.88	9.81	6.36	3.91	2.69	2.94	4.09	6.36
24A	9.31	11.56	13.89	14.21	11.62	10.18	6.77	4.51	3.30	3.50	4.68	6.47
24B	9.21	10.91	13.29	12.96	10.16	8.77	6.59	5.41	4.95	5.06	5.92	6.77
24C	9.19	11.10	13.74	13.97	11.09	9.72	6.91	4.85	3.95	3.94	4.87	6.67
26A	9.51	11.23	13.45	13.79	11.06	9.54	6.92	4.88	3.54	3.83	5.23	7.02

Table 4-4 Pan factors for open water evaporation and catchment evapotranspiration

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Lake evaporation	0.81	0.82	0.83	0.84	0.88	0.88	0.88	0.87	0.85	0.83	0.81	0.81
Catchment evapotranspiration	0.80	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.80	0.80	0.80

Table 4-5 Crop factors for vegetation types

Vegetation type	Crop factors											
	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Costal Tropical Forest	0.67	0.69	0.75	0.75	0.75	0.74	0.69	0.61	0.56	0.40	0.51	0.60
Inland Tropical Forest	0.73	0.78	0.78	0.78	0.78	0.75	0.70	0.65	0.50	0.40	0.55	0.65
BushVeld	0.51	0.56	0.59	0.59	0.59	0.58	0.50	0.44	0.32	0.27	0.35	0.45
False Bushveld	0.48	0.58	0.60	0.62	0.62	0.58	0.53	0.38	0.25	0.20	0.23	0.35
Karoo and Karroid	0.41	0.46	0.50	0.50	0.50	0.48	0.46	0.37	0.25	0.20	0.22	0.33
False Karoo	0.36	0.45	0.50	0.50	0.50	0.46	0.36	0.26	0.21	0.20	0.20	0.27
Temperate and Transitional Forest and Scrub	0.58	0.61	0.61	0.61	0.60	0.60	0.57	0.46	0.36	0.29	0.36	0.48
Pure Grassveld	0.43	0.56	0.62	0.62	0.62	0.55	0.43	0.28	0.20	0.20	0.20	0.27
False Grassveld	0.53	0.65	0.73	0.73	0.73	0.67	0.61	0.43	0.24	0.20	0.27	0.41
Fynbos	0.60	0.60	0.60	0.60	0.55	0.55	0.55	0.45	0.40	0.20	0.35	0.50
False Fynbos	0.55	0.55	0.55	0.55	0.55	0.50	0.50	0.40	0.35	0.20	0.35	0.50

Actual evapotranspiration (AET) Water is not always readily available for evapotranspiration. Over many rural surfaces there are times, notably on a summer afternoon, when the soil and plants are incapable of moving water to the surface ready for evaporation or transpiration as fast as the atmosphere can do the evaporation. Bare soil surfaces begin to dry out and plants begin to wilt. Their rate of evapotranspiration is termed actual evapotranspiration, which will be less than the potential evapotranspiration. Many investigators have used a soil-moisture extraction function or coefficient of evapotranspiration, *f*, which relates the actual rate of evapotranspiration to the potential rate of evapotranspiration based on some function of the current soil moisture content and the water-holding capacity (Haan, 1972)

$$AET = f * PET \quad (4\text{-}2)$$

$$f = wc / wc^* \quad (4\text{-}3)$$

Where *f* is the function in which the ratio of evapotranspiration to potential evapotranspiration is proportional to the current moisture level. It has been applied when budgeting with monthly climate values and is used in this study (Shuttleworth, 1993 and Dingman, 1994). This function predicts lower evapotranspiration rates than a function with a breakpoint that may offset (to some degree) the low rainfall intensities resulting from the use of monthly averaged rainfall. *wc* denotes the current soil water moisture *and wc** the water holding capacity.

4.2.5 Borehole information from NGDB

4.2.5.1 Borehole distribution and usability

Borehole yield or the exploitation discharge is the most concerned part of groundwater discharge of TMG aquifers. A total of 35151 boreholes are found in NGDB that located in the TMG area, from which the TMG-related boreholes have been carefully sorted out based on their locations, drilling depth, geological formations, hydrological characteristics, and etc. The following procedures have been carried out to sort out TMG-related boreholes. However misjudges might occur since only very simplified information is available for most boreholes.

- As the statistics of borehole discharge rate will be used in the quantification of the regional discharge of the TMG aquifer, boreholes without information on discharge rate are excluded.
- For the convenience of study, boreholes are grouped into outcrop-boreholes and non-outcrop-boreholes. Boreholes located on the TMG outcrop area are termed the outcrop-boreholes, while the remainder called the non-outcrop-boreholes.
- The outcrop-boreholes are all TMG-related and they are easy to sort out using the "Select by location…" function in ArcGIS. Three subgroups of outcrop-boreholes are identified respectively from the spatial selection with the outcrop of three sub-units of TMG aquifers, Nardouw, Peninsula and Piekenierskloof. There are 1139 boreholes drilled on the outcrops of

Nardouw Subgroup, 622 on the outcrops of Peninsula Formation and 209 on the outcrops of Piekenierskloof.

- Though most of the boreholes were drilled in the non-outcrop area of TMG, because of the limited depth of these boreholes, almost all of them don't penetrate into TMG, therefore are irrelative to this study. After thorough filtering according to their geological logging information together with their location, among the boreholes located in the non-TMG outcrop area, only 173 were drilled to Nardouw subgroup and 50 to Peninsula Formation. Most of the non-TMG outcrop boreholes were drilled in the contact zones of TMG and the adjacent Cedarberg Formation or Bokkeveld Group.

Fig. 4-8 shows the spatial distribution of the sorted out TMG-related boreholes and the depth statistics of them are listed in Table 4-6. The water level data of all the sorted-out boreholes are unevenly distributed both spatially and temporally and can't be used to do the regional analysis. However local analysis in some specific areas can be performed if the water level data in those areas are preferable. The discharge rates of the boreholes are adopted to do the regional groundwater discharge estimation.

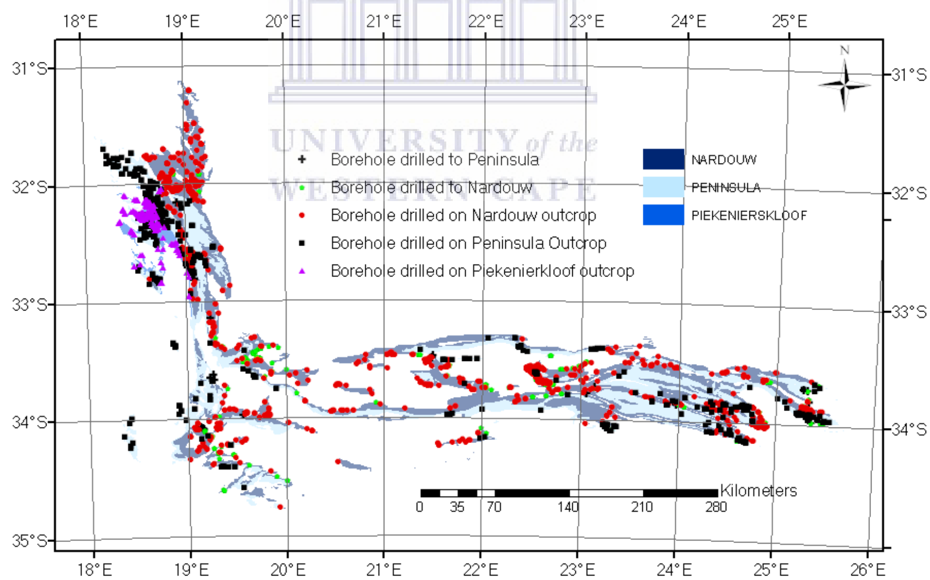


Fig. 4-8 The spatial distribution of TMG-related boreholes

Table 4-6 Depth statistics of TMG related boreholes

TMG related Boreholes		**Number**	**Percentage on depth range**						
			<50	**50-100**	**100-200**	**200-300**	**300-500**	**>500**	**Unknown**
Outcrop	Nardouw	1139	20.9%	38.7%	28.9%	4.7%	0.2%	0.2%	6.4%
	Peninsula	622	14.6%	32.6%	41.3%	2.7%	0.3%	0.0%	8.4%
	Piekenierskloof	209	14.4%	31.1%	36.4%	1.0%	0.0%	0.0%	17.2%

Non Outcrop	Nardouw	173	0.0%	55.5%	37.0%	7.5%	0.0%	0.0%	0.0%
	Peninsula	50	0.0%	6.0%	82.0%	6.0%	4.0%	2.0%	0.0%
Sum		2193	16.4%	36.9%	35.0%	4.1%	0.3%	0.1%	7.3%

4.2.5.2 Springs issuing from TMG

A lot of springs are issuing from TMG, which is one of the impressive features of it. Meyer (2002) contributed a detailed description and classification of these springs. According to the mode of occurrence, three types of springs have been identified as shallow circulating springs, lithology controlled springs and fault controlled springs. In TMG area, 501 springs are identified with the depth of "0.01m" in the National Groundwater Database (NGDB, 2005) in TMG area, among which 103 springs located in the TMG outcrop area are assumed TMG-related (Fig. 4-9). Because of the insufficient attributes description of these springs, it is difficult to classify them into the abovementioned three types.

4.2.5.3 Hot springs

Due to their specific hydrogeological significance the eleven more important and well-known fault controlled hot springs are separately discussed here. It is interesting that these springs are distributed along the Cape Fold Belt and forming a remarkable incurvature (Fig. 4-9). Five hot springs are located in the limited syntaxis domain, which may indicate more intensive and deeper fracturing in that domain compared to the rest. The main characteristics of these springs are listed in Table 4-7.

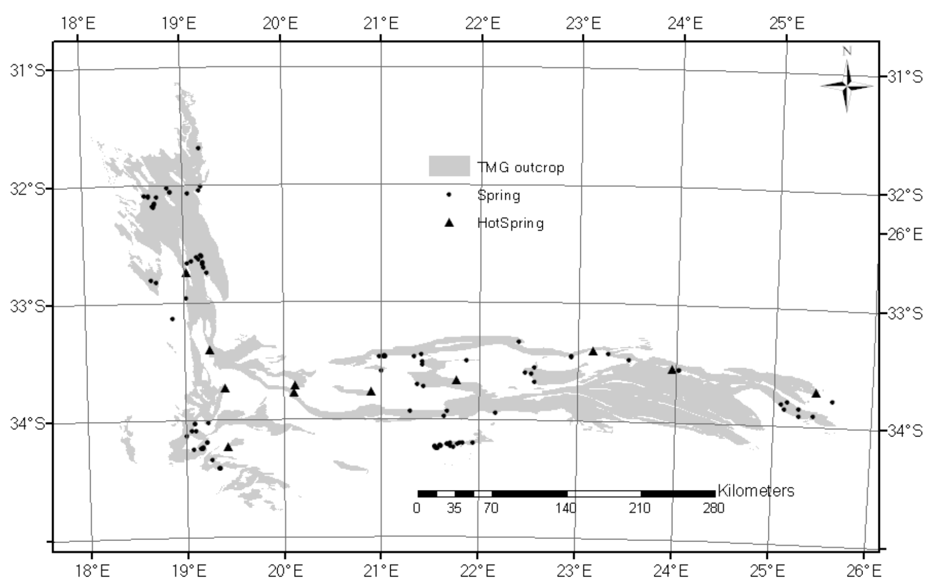


Fig. 4-9 The spatial distribution of TMG-related springs and hotspring

Table 4-7 Main information of TMG-related hotsprings (After Meyer, 2002)

Name	Temp (°C)	Yield (l/s)	Cond. (mS/m)	Probable depth of circulation (m)	Classification of thermal water	Geological setting
The Baths	43	29	8	2000	Hyperthermal	Situated on an E-striking fault in Peninsula Formation (TMG) sandstone, on the western limb of a deep syncline on the contact with the Cedarberg Shale Formation.
Goudini	40	11	7	1700	Thermal	Situated on a NNW-striking fault in Peninsula Foramtion sansstone near the contact with Bokkveld group shale.
Brandvlei	64	127	8	3600	Hyperthermal	Situated on a NE-striking fault in Nardouw Subgroup sandstone on or close to the contact with Bokkeveld Group shale
Caledon	37	9	20	1600	Thermal	Situated on an E-striking fault. Peninsula Formation sandstone faulted against Bokkeveld Group shale.
Avalon	43	38	11	2000	Hyperthermal	Situated on an E-striking fault. Nardouw Subgroup sandstone faulted against Bokkeveld Group shale.
Baden	38	37	10	1500	Thermal	Situated on an ill-defined E-striking fault in Nardouw Subgroup sandstone on the contact with bokkeveld Group shale.
Warmwater-berg	45	9	26	2100	Hyperthermal	Situated on a NE-striking fault. Nardouw Subgroup sandstone faulted against Bokkeveld Group shale.
Calitzdorp	50	8	31	2500	Hyperthermal	Situated on a NE-striking fault. Nardouw Subgroup sandstone faulted against Bokkeveld Group shale.
Toverwater	44	11	15	2000	Hypothermal	Situated on the E-striking Cango fault. Peninsula Formation sandstone faulted against Enon Formation (Uitenhage Group) conglomerate.
Studtis	24	31	18	480	Hypothermal	Situated on a NE-striking fault. Nardouw Subgroup sandstone faulted against Bokkeveld Group shale.
Uitenhage	23	45	34	400	Hypothermal	Situated on an ESE-striking fault in Peninsula Formation sandstone, on or close to the contact with Kirkwood Formation (Uitenhage Group). Yield fluctuates in accordance with abstraction from aquifer.

4.3 Demarcation of confined and unconfined aquifers

Though Weaver (2002) stated that there are no confining units in the TMG on a regional scale, in the sense of resource evaluation, confined and unconfined aquifers could be demarcated according to their geological settings in a traditional way. This can be done in GIS easily based on their respective geological and buried attributes.

Basically the TMG deposit area can be divided into TMG outcrop areas and non-TMG outcrop areas. In TMG outcrop areas, the subdivision of Nardouw outcrop and Peninsula outcrop is applied. In Nardouw outcrop areas, Nardouw aquifer can be attributed to unconfined aquifer and Peninsula is confined by the overlying Cedarberg Aquitard, while in Peninsula outcrop areas Nardouw formation and Cedarberg formation has been denuded and Peninsula formation is exposed to the surface, therefore Peninsula aquifer is unconfined. In non-TMG outcrop areas, both Nardouw Subgroup and Peninsula Formation are overlain by Bokkeveld Group, therefore both Peninsula and Nardouw Formations are confined aquifers due to the overlying layer as Gydo Formation is usually regarded as an aquitard. The delineation is sketchily showed in Fig. 4-10.

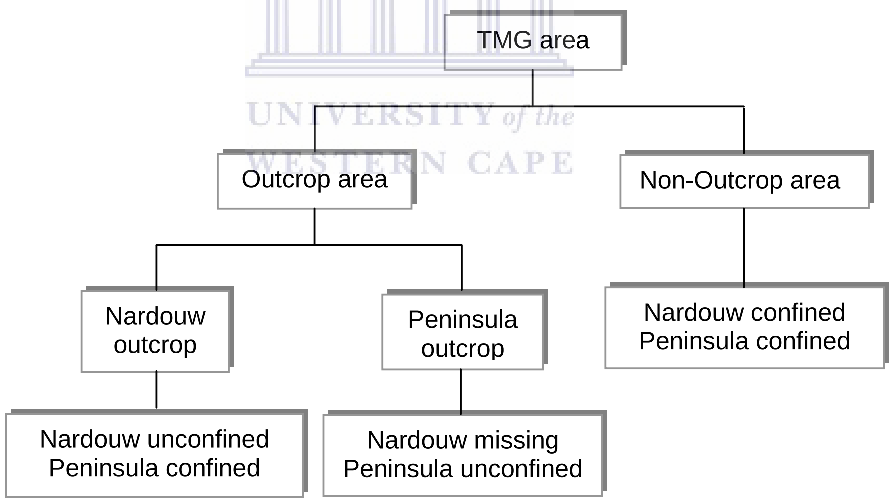


Fig. 4-10 Demarcation of confined and unconfined aquifer in TMG area

4.4 Recharge estimation

As aforementioned, it is assumed that only the TMG outcrop areas can receive the precipitation as recharge to the groundwater reservoir of TMG aquifers. This probably does not introduce significant error for groundwater recharge estimation in the whole TMG area, in that hydraulic relations seldom occur between TMG and other geologic formations unless large geologic structures exist and connect TMG with these formations. Hence only the TMG outcrop areas are selected as the study area in recharge estimation.

Various approaches have been applied in the recharge estimation in TMG areas, most of which were conducted on local scale or field sites. Soil water balance could be the most common and reasonable method to estimate groundwater recharge on a regional scale (Barringer and Lilburne, 1999; Reed et al., 1997). Based on the physically conceptual model it simulates the hydrological procedures involved in a soil water budget with the knowledge of relationships of components that participate in these processes. The components commonly include precipitation, actual evapotranspiration, runoff, soil moisture and recharge. When concerning about the relationship among these components, some simplified empirical function or formula are applied and are appropriate for providing a reasonable solution to a large-scale estimation. With the improvement of computing power and GIS technique, it is possible to model the spatially and temporally distributed hydrological processes and present the result in the same way. Soil water balance is seldom used in TMG area because the TMG rocks are characterized by the thin overlying soil layer and high-fractured sandstone. This study could be an attempt for its application. With limited knowledge of the hydraulic dynamic processes in the fractured rock zone, in this study only the hydrological process in the upper soil zone, rather than the whole recharge process are considered. Thereafter the estimated result could be more accurately regarded as recharge potential or an upper limit of the actual recharge. The term surplus or infiltration other than recharge is used to denote this value, which implies that the surplus of soil water could percolate further to the bedrock.

4.4.1 Model Description

A simple algorithm is used to predict soil water storage, evaporation, runoff, and soil water surplus in this model. Surplus is precipitation that does not evaporate or remain in soil storage or runoff by surface flow or sub-surface flow. It is the water quantity that infiltrates into the bedrock under the soil layer when the soil is saturated with water, after which it will be redistributed in the rock system, some

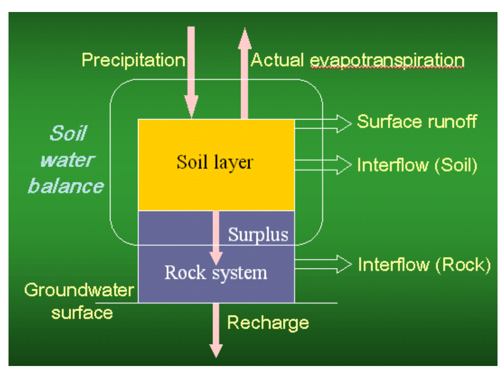


Fig. 4-11 Concept of the soil water balance model

percolates into the groundwater, some forms lateral flow (interflow) and flow out of the aquifer along fractures. The concept of this model is illustratively showed in Fig. 4-11. The conservation of mass equation for soil water can be written as follows (Reed et al., 1997):

$$\frac{\partial w}{\partial t} = P - E - R - S \qquad (4\text{-}4)$$

In Equation (4-4), S stands for soil water surplus, P precipitation, E evaporation, R surface runoff, w soil moisture, and t time. Snowmelt was not considered in these computations because of the shortage of data.

4.4.2 Soil water balance modeling

The computing procedure for soil water storage is described by Equation (4-5) as below (Reed et al., 1997).

$$wc_i = wc_{i-1} + P_i - R_i - f_{i-1}PET_i \quad \text{if } wc_i < wc^*$$
$$S_i = wc_i - wc^* \text{ and set } wc_i = wc^* \quad \text{if } wc_i > wc^* \qquad (4\text{-}5)$$

Where wc_i is the current soil moisture, wc_{i-1} is the soil moisture in the previous time step (month), P_i precipitation, R_i runoff, PET_i potential evapotranspiration, S_i the surplus in a given month, f the soil-moisture extraction function and wc^* the water-holding capacity. When evaluating Equation (4-5), if wc_i drops below zero, then wc_i is set equal to 0.01; if $wc_i > wc^*$, then the surplus for that month is $wc_i - wc^*$ and wc_i is set equal to wc^*. The soil-moisture extraction function $f = wc/wc^*$ was used for this study.

If the initial soil moisture is unknown, which is typically the case, a balancing routine is used to force the net change in soil moisture from the beginning to the end of a specified balancing period (12 months) to zero. In this study the initial soil moisture is set to the water holding capacity and budget calculations are made up to the time period ($N+1$). The initial

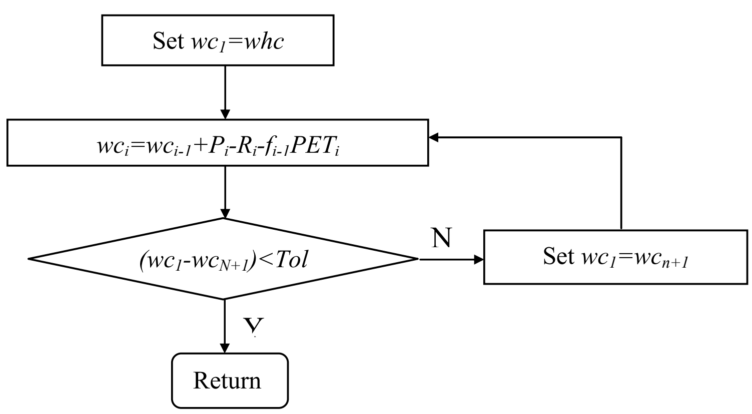


Fig. 4-12 Flow chart of soil water balance computation

soil moisture at time 1 (wc_1) is then set equal to the soil moisture at time $N+1$ (wc_{N+1}) and the budget is re-computed until the difference (wc_1 - wc_{N+1}) is less than a specified tolerance. The flow chart of the computation is showed in Fig. 4-12.

In this study, in order to be consistent to the recorded data, October is set as the initial time step or the first month that the computing starts with. Therefore the soil moisture in October is set to the water holding capacity. Equation (4-5) is programmed in Excel to calculate other months' water surplus or infiltration. Each month's soil moisture as well as surplus is calculated with the previous month's soil moisture content and the current month's precipitation, runoff, actual evapotranspiration, etc. when September's surplus is calculated out, the computing is not stopped but continued to calculate another October's value. That is to say, the second October's soil moisture value is modeled by program while the first October's value is pre-given. The algorithm of Equation (4-5) is an iteration process. The control conditions for the simulated values are set as described above. Besides, the difference between the second and the first October's soil moisture values should be less than 1mm, which is the only control condition for the iteration process.

4.4.3 Data processing

The source data layers used in GIS are listed in Table 4-8. The input maps, i.e. Rainfall, Evaporation, Soil and Runoff, are derived by integrating relative data layers. Then the four maps are overlaid to generate the first-step result map, in which the TMG outcrop areas are divided into thousands of hydrologically equivalent polygons, each polygon is homogeneous and representing the same hydrological features, but different from others. The attribute table

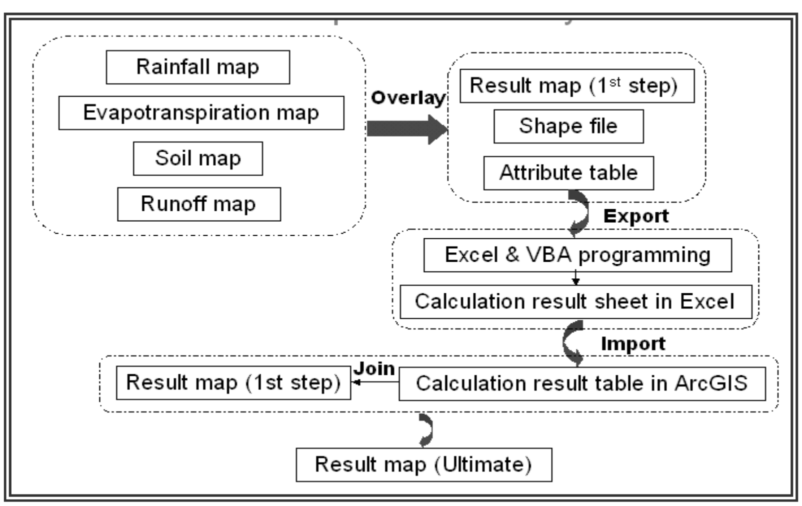


Fig. 4-13 Flow chart of data processing

of the first-step result map is exported and imported into Excel, and then the soil water balance calculation described in section 4.3.2 can be performed by executing the subroutine "CalculateSoilWater" compiled in VBA embedded in Excel, from which the monthly soil water, surplus, actual evapotranspiration for each polygon could be calculated. After the calculation the result sheet in Excel is imported into ArcGIS and linked to the first-step result map. The ultimate result maps can be worked out by presenting the calculated result of soil water, surplus and actual evapotranspiration. The procedures are summarized by a flow chart as Fig. 4-13.

Table 4-8 Source data layers for recharge estimation

Item	Data layer	File Type
Rainfall	Rainfall isoline (MAP)	shape file
	Rainfall zone	shape file
	Rainfall monthly percentage table	.dbf table
Evaporation	Evaporation isoline (MAE)	shape file
	Evaporation zone	shape file
	Evaporation monthly percentage table	.dbf table
	Vegetable	shape file
	Crop factor	.dbf table
Soil	Soil properties	shape file
Runoff	Runoff zone and value (MAR)	shape file
	Runoff monthly percentage table	.dbf table

4.4.4 Results and discussion

The results from the soil water balance modeling are monthly values of surplus from October to September. The result maps are created with mean annual surplus rate (percentage of MAP), mean annual surplus (mm) and mean annual surplus volume (Mm^3) of TMG outcrop areas, as showed in Fig. 4-14, Fig. 4-15, and Fig 4-16. The modeling results are also summarized by quaternary catchment in Appendix 1. The calculated total soil water surplus or the upper limit of recharge volume is about 4.36×10^9 m^3 per annum, and the mean annual surplus in TMG outcrop areas is calculated as 115mm. This value is large when compared with the recharge estimations listed in Table 1-1**.** This is because that the hydrological process in rock system is not taken into account in this model, as showed in Fig 4-11. Rock interflow could be a significant part of water balance in some cases, especially in TMG area. It is more dependent on the geological structure and the combination of the related rock formations. With the common baseflow separation method, the part of interflow can't be separated from the total stream flow successfully. Therefore the entire water surplus from soil to the underneath TMG deposit is calculated out as potential recharge capacity or an upper limit of recharge in this area.

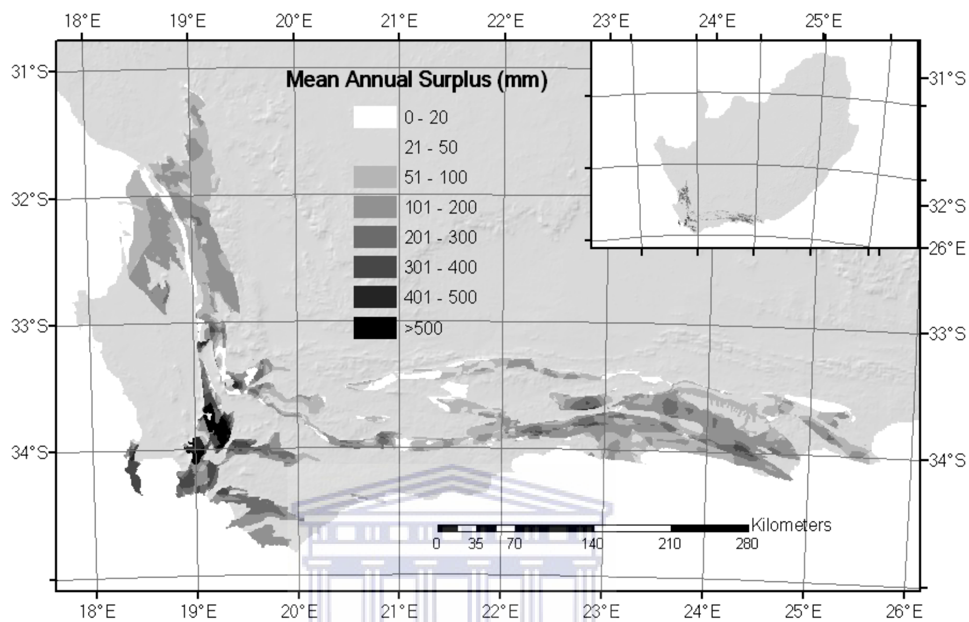


Fig. 4-14 Mean annual surplus (mm) of TMG outcrop area

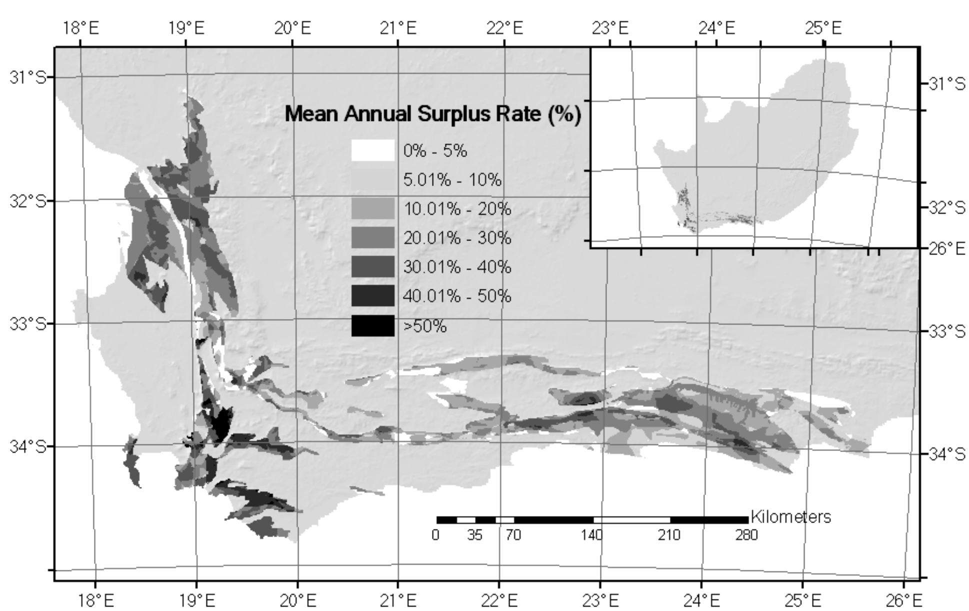


Fig. 4-15 Mean annual surplus rate (%) of TMG outcrop area

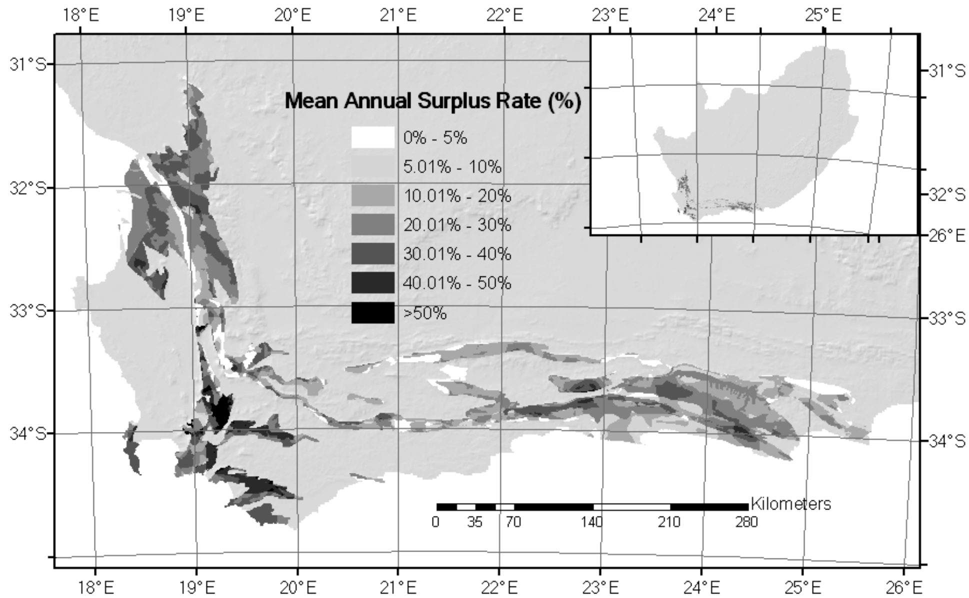


Fig. 4-16 Mean annual surplus rate (%) of TMG outcrop area

Alternative recharge estimation in TMG outcrop areas derived from integrated approaches was conducted by Wu (2005), which could be used as calibration of the present estimation and help to determine the recharge quantity in this study. He estimated that the recharge volume is about 1.12×10^9 m^3 per annum and the mean annual recharge in TMG outcrop area is 29.74mm.

4.5 Storage capacity estimation

Groundwater becomes a valuable resource when the water discharges from aquifers yields water supply to wells, springs, or streams, when the discharged water is perennial or seasonally persists long enough to meet a specific requirement, when the mineral substances dissolved by water do not reach much concentration to make the water unfit for desired use, and when the practical exploitation of the groundwater in an area does not cause environmental problems such as over depression of water table, degradation of vegetation or wetland, or encroachment of sea water, ect. For an aquifer, the questions of how much there is

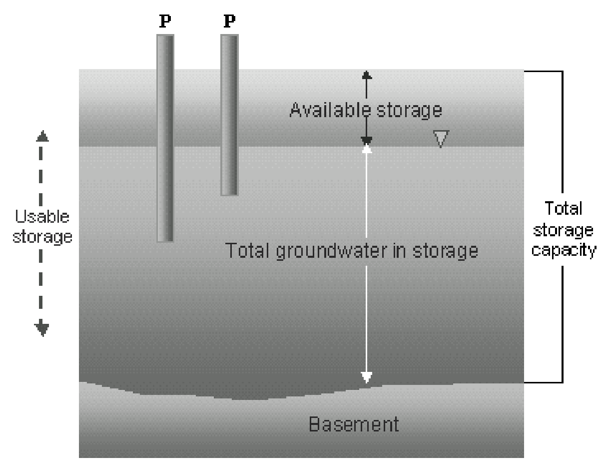


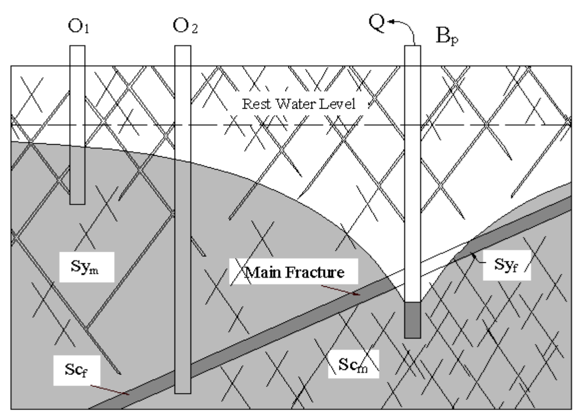
Fig. 4-17 Total storage capacity, usable storage capacity and available storage capacity (after CWR, 2003)

and how more can be available are important. Groundwater storage capacity of an individual catchment or on a regional scale is cared about by private citizens, water resource planners, and politicians (CWR, 2003). There are many terms and concepts associated with the groundwater storage capacity. In this study, the storage capacity of TMG is classified into total groundwater capacity, usable groundwater capacity and available groundwater capacity according to the groundwater buried condition and technical exploitation condition. The classification is showed in Fig. 4-17. The estimation of groundwater storage capacity is simple if data are available. It is determined by multiplying the volume of associated aquifer by the average storativity.

4.5.1 Storativity of TMG aquifers

As mentioned in Chapter 1, storativity is the general term of specific yield and storage coefficient. In most of the TMG studies, storativity, instead of specific yield or storage coefficient, is commonly used to describe the aquifer storage properties.

The storativity of fractured rock aquifer is scale-dependent, and this is the case in the TMG aquifers. On a microscopic scale, the storativity can be estimated by core sample porosity, which accounts for the storativity of both fractures and matrix rocks at scale of less than one meter. Very few porosity analyses of the TMG core samples have been carried out (Table 4.9), using volumetric method. The result shows that the porosity of the TMG sandstones ranges from 1.0~3.6% with an average of 2.5 (courtesy of Gerrit Van Tonder and Lixiang Lin, 2007). These values greatly depend on both laboratory methods and selections of core samples. Other factor influences the measurement of the porosity is the stress release of the core samples, which makes the in situ measurement difficult and variation of the porosity at depth inconspicuous (Table 4.9).



Sy – Specific Yield; m – Rock Matrix;
Sc – Storage Coefficient; f – Fracture
Fig. 4-18 Variable storativity conditions in the vicinity of a production borehole in a fractured-rock aquifer (after Woodford ,2002)

On a mesoscopic scale or a site scale, storativity values are usually derived from pumping test analyses. Under a steady flow condition, the storativity values derive from pumping tests may account for the aquifer porosity at a scale of several meters to hundred meters. However groundwater flow in the fractured rock is mostly controlled by the characteristics of fractures, such as orientation, density, aperture, and connectivity. In terms of fracture extension and connection, Woodford (2002) described the storativity of a pumped fracture with an explanative diagram (Fig. 4-18). He stated that storativity of a fracture in a pumping process is complex and varies spatially and temporally. When the piezometric-level is above the fracture, the confined storage coefficient may be applied to the fracture while the unconfined specific yield applies to the dewatered fracture. Table 4-9 lists the storativity estimated from some representative pumping tests conducted in the TMG aquifers. These pumping test results yield the storativity values widely ranging from 1×10^{-4} – 1.2×10^{-2} which are about two to three orders of magnitude less than those of core sample.

Table 4-9 Porosity derived from core samples and pumping tests

Type	Sample Depth [m]	Porosity range [%]	Average porosity[%]	Reference
Core samples	3322 -3420 [7 samples]	1.9 – 2.3	1.5	Core samples of Soekor boreholes, after Roswell and De Swardt, 1967
	122 – 154 [11 samples]	0.6 – 1.7	1.4	
	1 – 152 [49 samples]	0.9 – 5.4	3.1	
	10 – 107 [7 samples]	1.2 – 3.0	2.2	
	42.5 – 135.5 (6 samples)	1.0 – 3.6	2.5	Core samples of Rasonville BH1, TMG
Pumping tests	Koo Valley	0.01 – 0.35	0.06	Pumping tests, Jacob
	Kammanassie	0.11 – 0.22	0.15	Kotze (2002)
	Boschkloof	0.1 – 0.01	0.05	Umvoto (2000)
	Gevoden	0.21 – 1.2	0.57	Pumping tests, Jacob

The storativity values estimated from pumping tests using the late drawdown data, where the elastic release stage is assumed to be over and fractures are assumed the main conduits to deliver flow into boreholes and the matrix porosity can be neglected. A simple way to estimate the porosity of TMG aquifers can be carried out by fracture measurement and statistics. The fracture measurements may be conducted on the surface of outcrop or on a rock block which has been moved away from the original position. A lot of fracture measurements have been done in various outcrop areas of TMG, such as Table Mountain, Rawsonville, Montague, etc. A wide porosity range from 0.041% to 0.52% is derived from these measurements. Note that the values of porosity are in the range of those from pumping tests. An example of such measurement is introduced here. A perfect rock block has been found in Kirstenbosch, Cape Town, which is identified to be a boulder of Peninsula Formation from the adjacent Table Mountain containing four sets of fractures, as shown in Fig. 4-19

The geometric size of the rock block is as follows,

S (Surface Area) = 3.397m^2, and

D (Average Thickness) = 0.423m,

from which, the volume of the rock could be calculated out as $V=S*D=1.438m^3$.

In this case only the visible fractures can be measured for the computation of the porosity. The surface fracture tracement of the rock block is shown in Fig. 4-20. Fracture porosity is defined as the ratio of total volume of fractures at the measurement scale to the volume of the rock mass. In general the porosity of a rock mass is the sum of fracture porosity and rock matrix porosity:

$$Nt = Nf + Nm(1-Nf) \qquad (4\text{-}6)$$

Where Nt, Nf, and Nm stand for total porosity, fracture porosity, and rock matrix porosity, respectively.

In this case, the rock matrix porosity is approximated to 0 since the primary interstice between the sand grains have been cemented. The orientation, spacing and aperture of the four sets of fractures are measured and listed in Table 4-10. The corresponding porosity are calculated out from these measurements and also listed in Table 4-10. A total porosity of 0.041% is finally decided for this rock block.

Fig. 4-19 A rock block of Peninsula Formation in Kirstenbosch

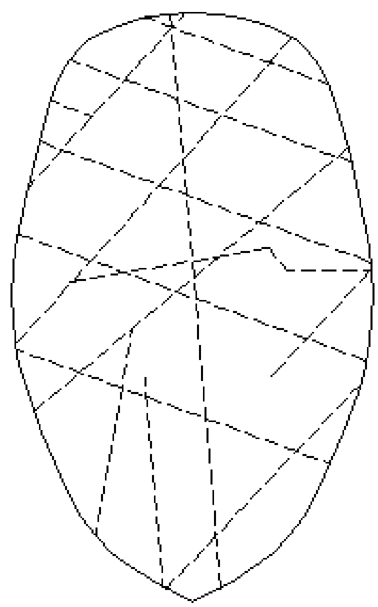


Fig. 4-20 The fracture tracement of the rock block

Table 4-10 Fracture measurements, statistics and derived porosity of the block

Sets	Orientation	Spacing (m)	Aperture (mm)	Porosity
Set 1	290°~320°	7.437	0.08	1.751E-04
Set 2	40°~50°	4.793	0.08	1.129E-04
Set 3	350°~20°	4.5643	0.05	6.717E-05
Set 4	70°~90°	1.280	0.15	5.652E-05
Total				4.117E-04

On a microscopic scale, the aperture of a fracture is proportional to fracture length (Zimmermann et al., 2003). However, on a macroscopic scale or a regional scale, the relationship between fracture aperture and fracture length follows power law with the exponent of 0.3~0.5 (Liu and Bodvarsson, 2001):

$$B = c \cdot L^{d}$$

Where B – fracture aperture, L - trace length, the constant *c* and *d,* which could be varied due to the statistics results. These relationships between fracture length and aperture imply that the porosity of a fractured rock may decrease drastically from a small scale to a large scale. In this study, the ETM^{+} imagery is used for the interpretation of lineaments which are identified to be the reflection of the subsurface fracture systems on the outcrop of the TMG sandstones

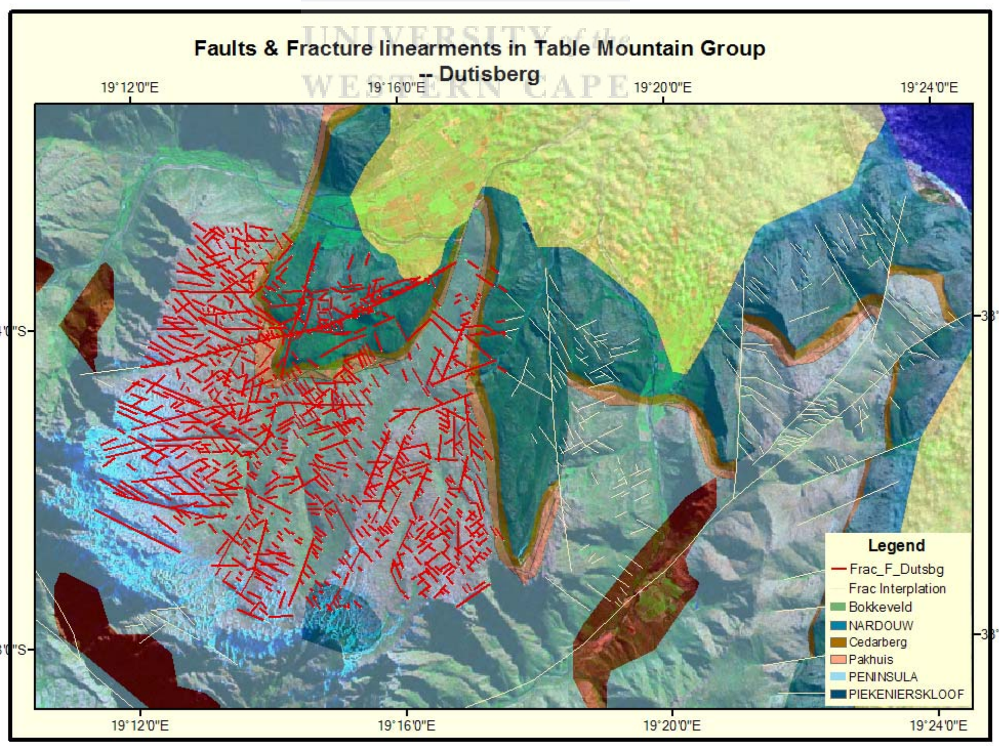


Fig. 4-21 Faults & Fracture lineaments in Table Mountain Group - Dutisberg

in Rawsonville (Fig. 4-21). The study area is 80.25 km^2 and 888 fractures with various lengths are cropped using software ArcGIS in which each fracture length can be computed. To calculate the fracture apertures, the constants c and d are specified as 1.01×10^{-4} and 0.42 respectively, based on the fracture statistics. As a result, the apparent porosity of the area is 1.24×10^{-8}.

On a regional scale, Weaver (2002) stated that there are no confining units in the TMG excluding the local conditions where Bokkeveld shale or Cedarberg shale overlies the TMG and the available water from the TMG is a combination of both storage coefficient and specific yield (S_c + S_y) with spatial variations. In a regional resource evaluation, the demarcation of aquifers described in Section 4.3 is applied for the assignment of storativity values, which means that the specific yield is assigned to the unconfined aquifers whilst the storage coefficient to the confined aquifers.

Though in most of the previous studies Peninsula and Nardouw Aquifers are not differentiated clearly when evaluating the hydrogeological parameters, significant differences between them do occur in the absence of permeable aquizones, which may connect the two aquifers. The Peninsula Aquifer usually outcrops at higher altitudes and is separated from the Nardouw by the Cedarberg Formation. They receive more precipitations and therefore more direct recharge. Groundwater flow paths and residence times are shorter, providing low EC/TDS groundwater. On the contrary, the Nardouw Aquifer receives less direct recharge and groundwater traveling has longer travel-times and therefore higher EC/TDS. The Peninsula Aquifer has lower shale content and is much more fractured than the Nardouw and the flow system is therefore more dynamic, i.e. more active flow circulation and recharge and less blocking of permeabilities from the products of shale weathering. Such differences can also be reflected in storativity of the two aquifers. Considering the differences, an assumption of 30% reduction in storativity is applied to Nardouw Aquifer compared to Peninsula Aquifer.

No determinate and consistent values of storativity of the TMG aquifers can be concluded from the review in Chapter 1, which is a common difficulty encountered in regional studies due to the storativity values are scale-dependent. In terms of groundwater usage, however, the value ranges may be primarily decided based on the previous researches. The range of high value of 10^{-3} to low value of 10^{-5} is assumed as the value range of the storage coefficient of confined Peninsula Aquifer, and the range of 5×10^{-3} to 1×10^{-4} is assigned to the specific yield of unconfined Peninsula Aquifer, which is shown in Table 4-11. These value ranges are generalized from the previous studies, which have not taken into the consideration of the depth effect of the TMG aquifers. For the sake of spatial variation of the aquifers, three scenarios (low, medium and high storage coefficient and specific yield) for the TMG storage capacity estimations will be conducted based on these values.

Table 4-11 Recommended storativity values for TMG aquifers

Aquifer Type	Range	Storativity	
		Specific yield (Unconfined)	Storage coefficient (Confined)
Nardouw	Low	7E-5	7E-6
	Medium	3.5E-4	7E-5
	High	3.5E-3	7E-4
Peninsula	Low	1E-4	1E-5
	Medium	5E-4	1E-4
	High	5E-3	1E-3

4.5.2 Thickness and regional distribution of TMG aquifers

Besides the storativity, the determination of thickness and regional distribution for the TMG rocks is the upmost task in groundwater storage capacity evaluation. On the other hand it could also be very "dangerous", because the underground geological setting cannot be visually available as the surface. The geological map and borehole data are the only data sources to build the subsurface geological settings, from which significant errors might be introduced by misjudgments of the people who interpret the geological map or by the spatial variability that cannot be reflected by the boreholes. In this study due to scarcity of subground geological information, the determination of the aquifer thickness has to be done in the abovementioned way. The following procedures are followed:

1) *Buildup of cross sections*

The purpose of the cross sections is to visualize, analyze and measure the variation in depth, thickness and altitude of the different formations of the Table Mountain Group (TMG) over the Cape Fold Belt. Regionally the key Formations/Subgroup control the TMG aquifer systems are Peninsula and Cedarberg Formations and the overlying Nardouw Subgroup with respect to their variation in lithology, outcrop and spatial distribution.

Generally the TMG is strongly compartmented by faults or fault zones created in Palaeozoic and reconstructed during Mesozoic tectonics. As results, two major regional faults i.e. the Worcester fault and Kango fault control the buildup frames of the TMG distribution to a very large extent. 8 geological profiles were therefore selected across these structures (Fig. 4-19 and Table 4-11) to encompass the variation in lithology and thickness of the TMG as well as the structural complexity of the Cape Fold Belt. Meanwhile, 21 small cross sections were located over the TMG to make up for representing the geological embarks in some typical domains/blocks (Fig. 4-21).

Datum collections and result productions for cross sections are from topographical and geological maps. Very few boreholes penetrated main aquifers in the TMG outcrop areas or touched TMG layers in Karoo areas, which makes it difficult to safely determine the top or bottom of the TMG layers and check up the accuracy of layer locations on the cross section maps. With detailed analyses of geological and structural information and topographic data, 8 principal cross sections (Fig. 4-22) and 21 small ones have been carried out, covering almost the whole study area and also the main structural domains.

Most of the works in this part are done manually on screen by capturing and reading the coordinates and elevation of the intersection points of cross section lines and the geological formations or elevation contour lines. Then the original coordination data and the relevant geological data were input into AutoCAD and the cross sections were built in the CAD format.

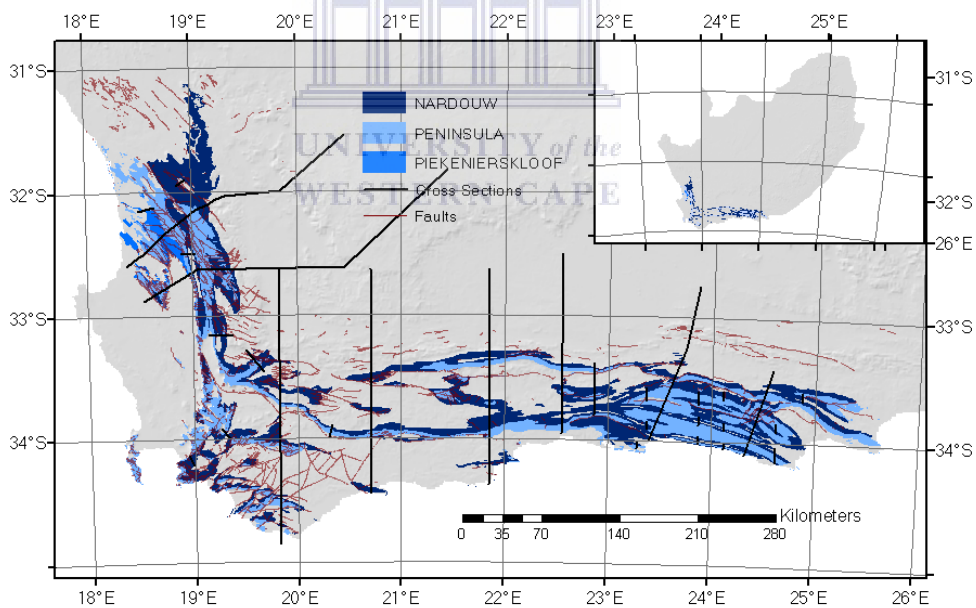


Fig. 4-22 The location of cross sections in TMG area

Table 4-12 Locations of Vertex along main Cross section lines

Cross section	Vertex on section line	Coordinate E (°)	Coordinate S (°)	Cross section	Vertices on section line	Coordinate E (°)	Coordinate S (°)
01	1	18.3884	-32.6094	02	1	18.5389	-32.8833
	2	18.5000	-32.5275		2	19.0544	-32.6233
	3	18.5380	-32.5000		3	20.4542	-32.6167
	4	18.7500	-32.3464		4	21.4389	-31.8264
	5	18.8852	-32.2500	03	1	19.8333	-34.8333
	6	19.0000	-32.1667		2	19.8333	-32.6667
	7	19.0709	-32.1383	04	1	20.7000	-34.4667
	8	19.1791	-32.1105		2	20.7000	-32.6167
	9	19.2236	-32.0771	05	1	21.8500	-34.3708
	10	19.3320	-32.0481		2	21.8500	-32.6333
	11	19.5000	-32.0339	06	1	22.5500	-32.5000
	12	19.7500	-32.0106		2	22.5500	-33.9500
	13	19.8611	-32.0000	07	1	23.3893	-34.0000
	14	20.0000	-31.8961		2	23.7500	-33.2500
	15	20.1947	-31.7500		3	23.8083	-33.0000
	16	20.2500	-31.7081		4	23.8661	-32.7500
	17	20.4552	-31.5530	08	1	24.3216	-34.1025
					2	24.5869	-33.4167

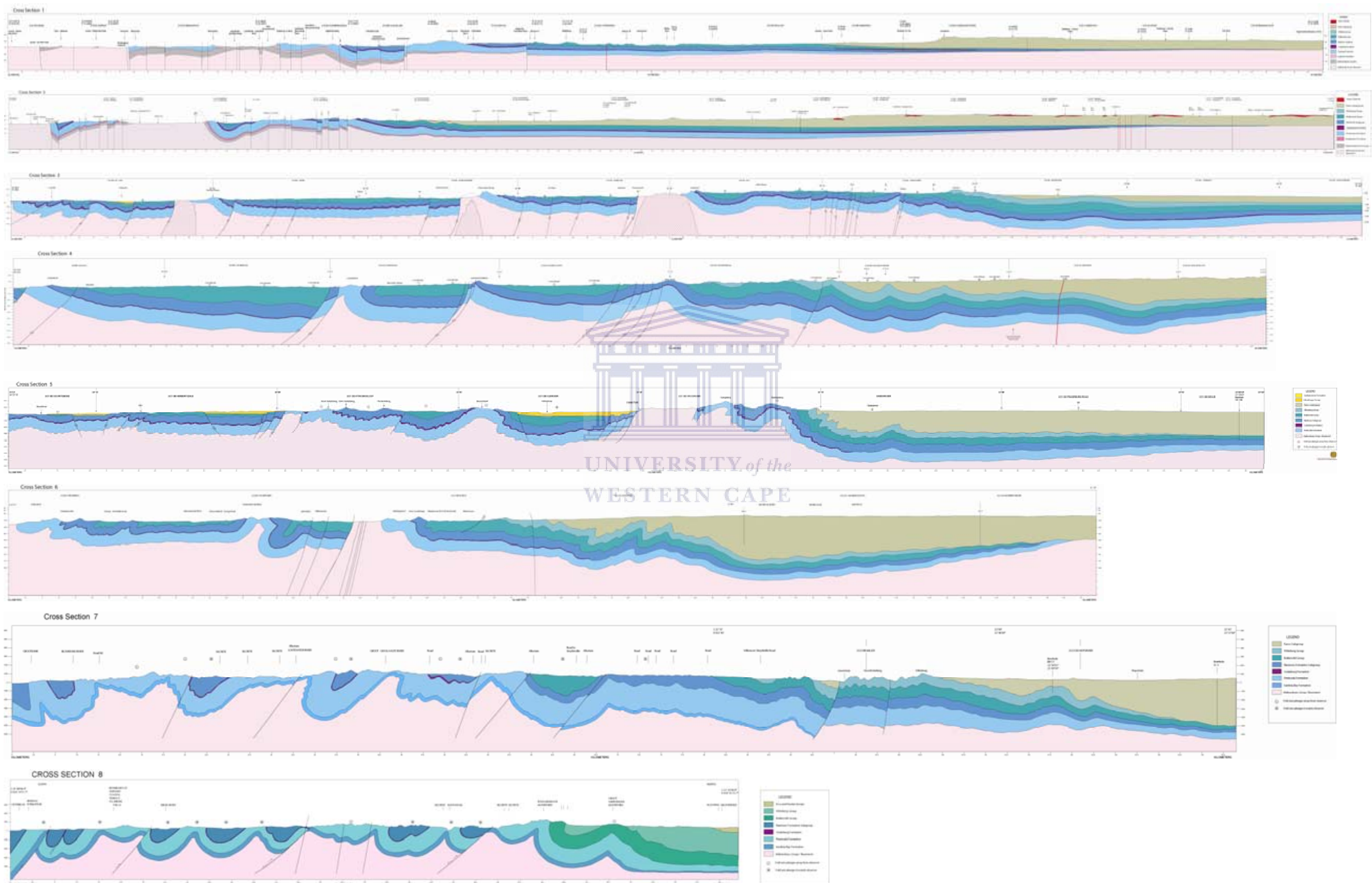


Fig. 4-23 Main cross sections (1- 8) through TMG area (completed by CGS, 2004)

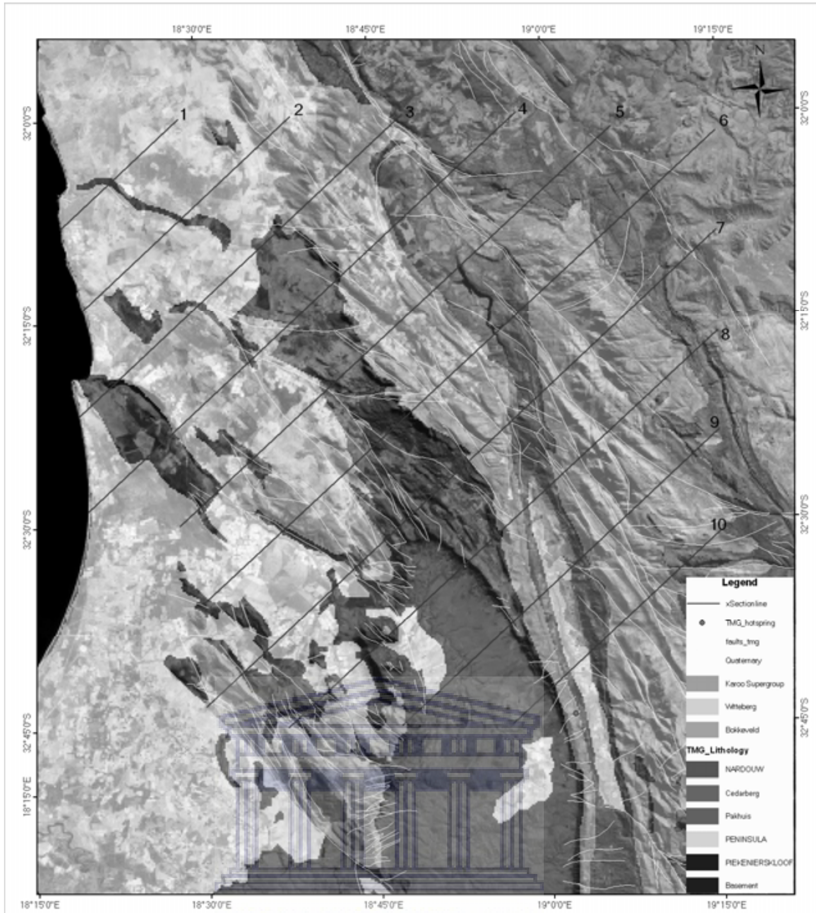
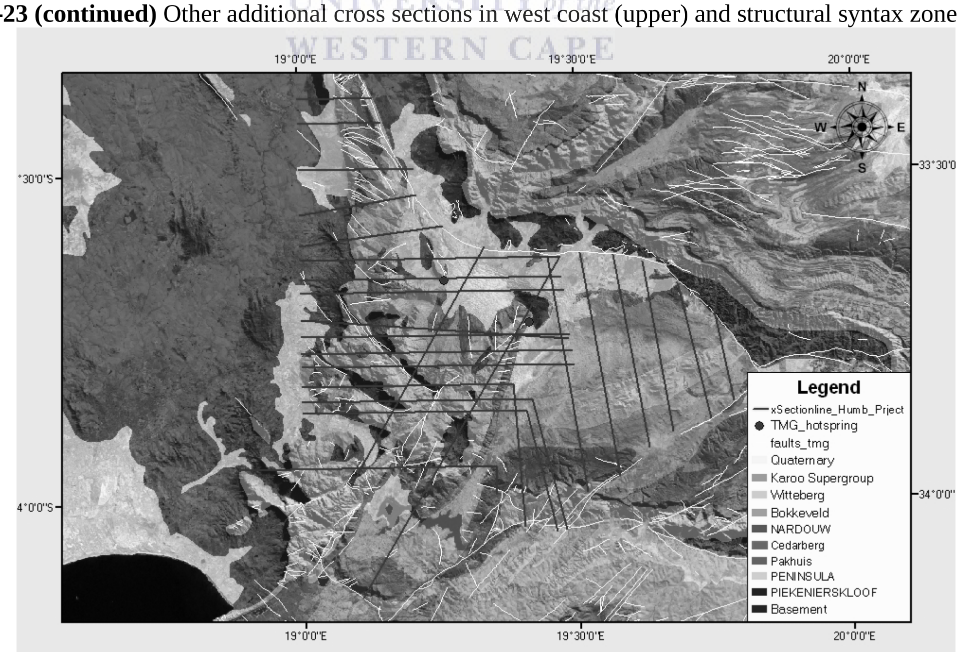


Fig. 4-23 (continued) Other additional cross sections in west coast (upper) and structural syntax zone (lower)



2) Data capture of cross sections

In the previous procedure, the reliability of the source data and the experience of hydrogeologist is uppermost important when interpreting the geological map. In this procedure, the carefulness and patience is prerequisite to make sure that as much as possible information can be captured from the cross sections, which is a time-consuming job. Each cross section was processed in the following way: vertical lines are made on the start location, the end location of the section and the structural change locations (e.g. the start, end, and axis of fold, fault and etc) along the section and then the control elevations (top elevation and bottom elevation) of each typical layers on each location are recorded. By doing the abovementioned work, point data with the top and bottom elevation through out the TMG are obtained for each typical layer. To avoid the possibly repeatedly work and curtail the workload, some simplifications can also be made. Typical layers only involve the two main aquifers (Nardouw aquifer and Peninsula aquifer), Cedarberg aquiftard and TMG basement. The resultant control elevation layers include top elevation of Nardouw aquifer, bottom elevation of Nardouw aquifer, top elevation of Peninsula aquifer, bottom elevation of Peninsula aquifer and top elevation of TMG basement. The point data are input into the interpolation software Surfer 7.0 to create the primary contours, from which the evenly and densely distributed point data are derived for the next step. Interpolation processes always introduce mistakes. Before the next procedure, these data are calibrated and corrected according to the spatial relationship between the typical layers, e.g. on each point, the top of Nardouw should not be lower than bottom of Nardouw, and etc.

3) Creation of TMG isobaths and isopaches

The evenly and densely distributed point data, as the result of previous procedure, were input into ArcGIS, in which the grid for each layer can be produced by using the spatial analyst extension. Then the resultant grid layers were trimmed by the border of the study area. Other processes include cutting out the non-TMG deposit area for all lays except top of TMG basement and cutting out the Peninsula outcrop area for top and bottom of Nardouw. Isobaths of the typical layers can be created by the resultant gridding maps, based on which the isopaches of the typical layers can also be created using raster calculation function in ArcGIS spatial analyst extension.

By this step, the determination of TMG thickness and spatial distribution is initially complete. However, due to the limitation of data source and the interpolation techniques, errors may be produced in any procedure abovementioned. Therefore more data sources are needed to calibrate the result.

As a whole the study on cross sections, isobaths and isopaches of TMG are restricted to a regional scale, through which an initial graphic visualization and understanding are attempted on the TMG aquifers, geological nature, and spatial relationships among TMG and its adjacent Groups/Formations. Hydrogeologically, the results (Fig. 4-23 to Fig. 4-30) carried out provide an elementary pattern of TMG aquifer systems to a certain extent and will serve as a powerful input for further studies.

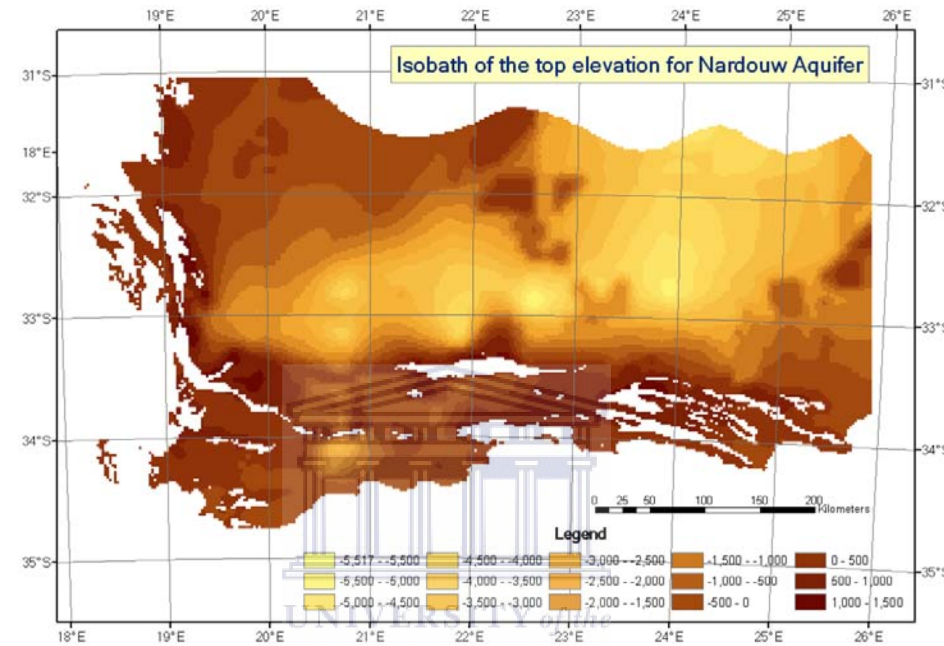


Fig. 4-24 Isobath of the top of Nardouw Aquifer

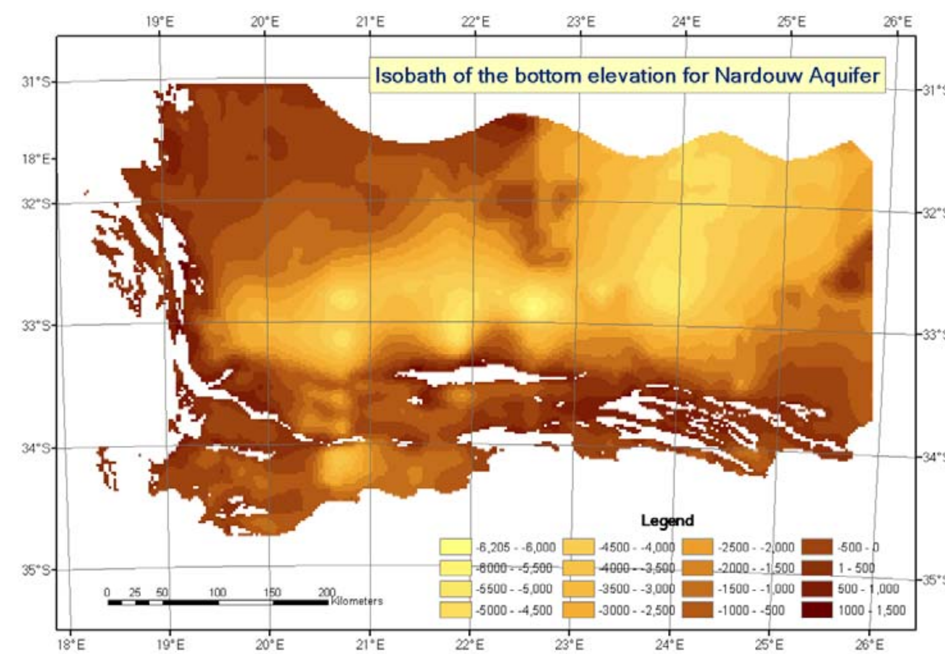


Fig. 4-25 Isobath of the bottom of Nardouw Aquifer

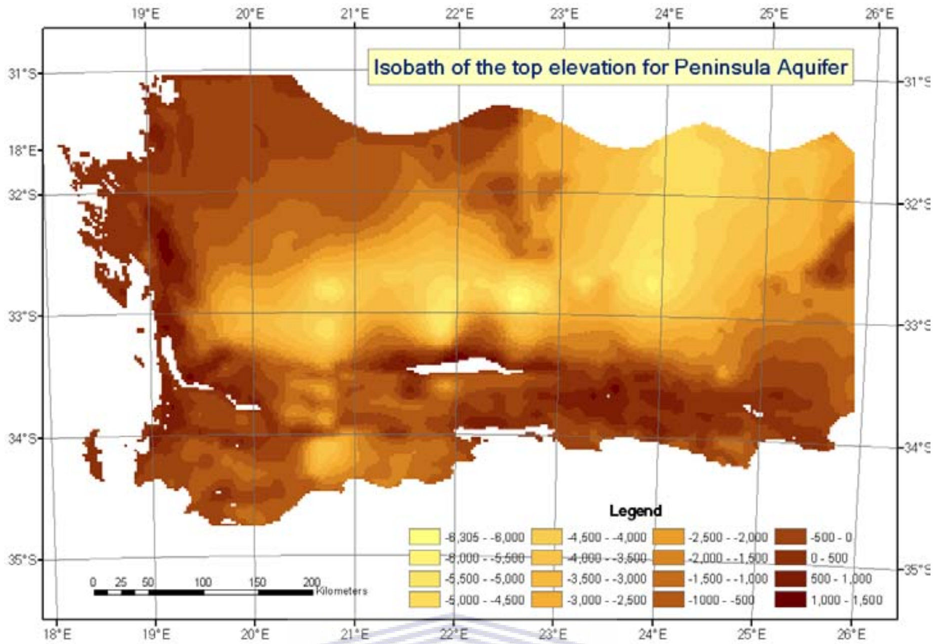


Fig. 4-26 Isobath of the top of Peninsula Aquifer

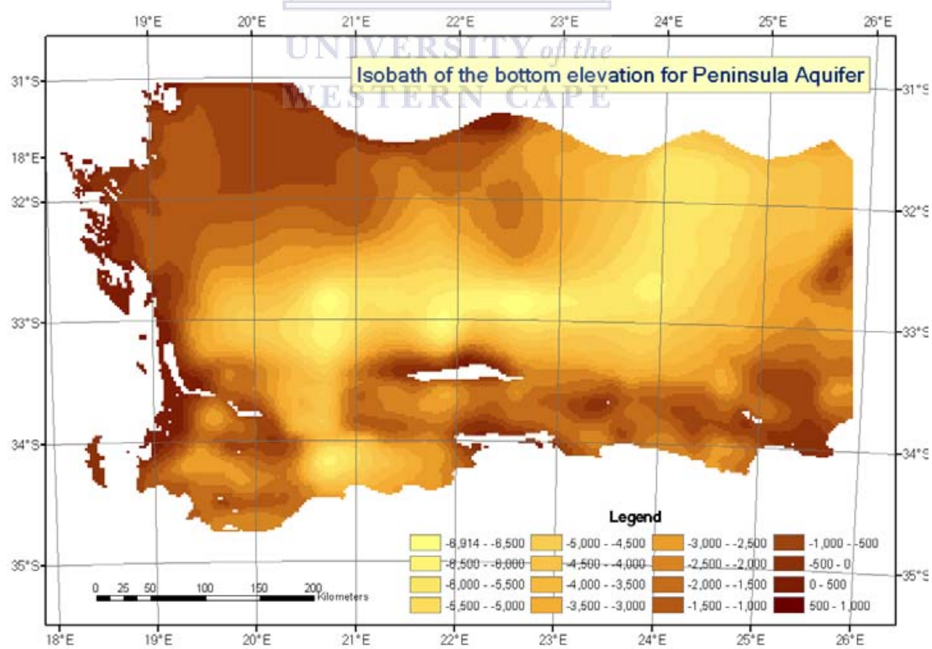


Fig. 4-27 Isobath of the bottom of Peninsula Aquifer

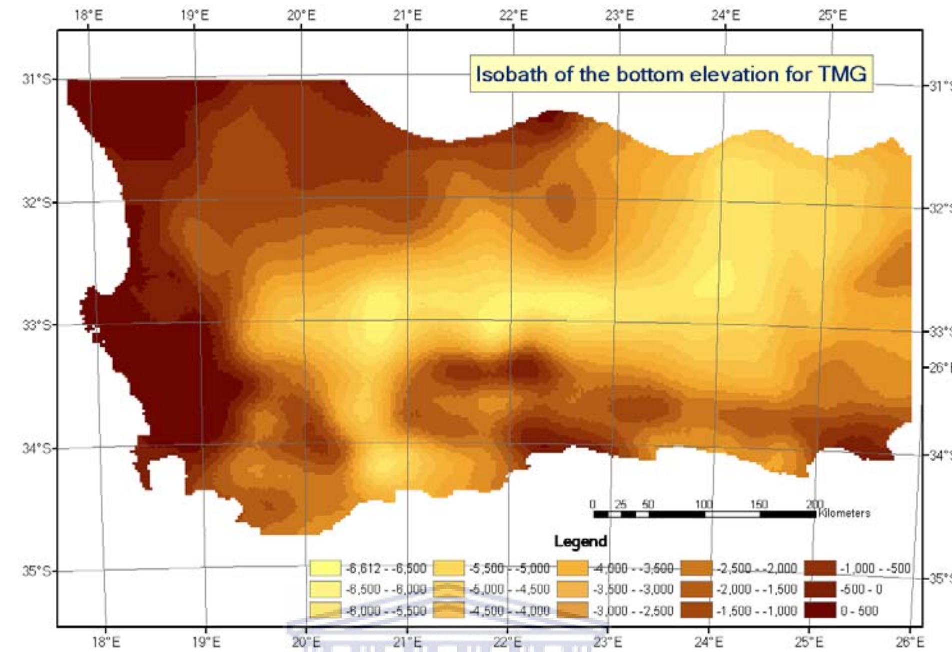


Fig. 4-28 Isobath of the bottom of TMG

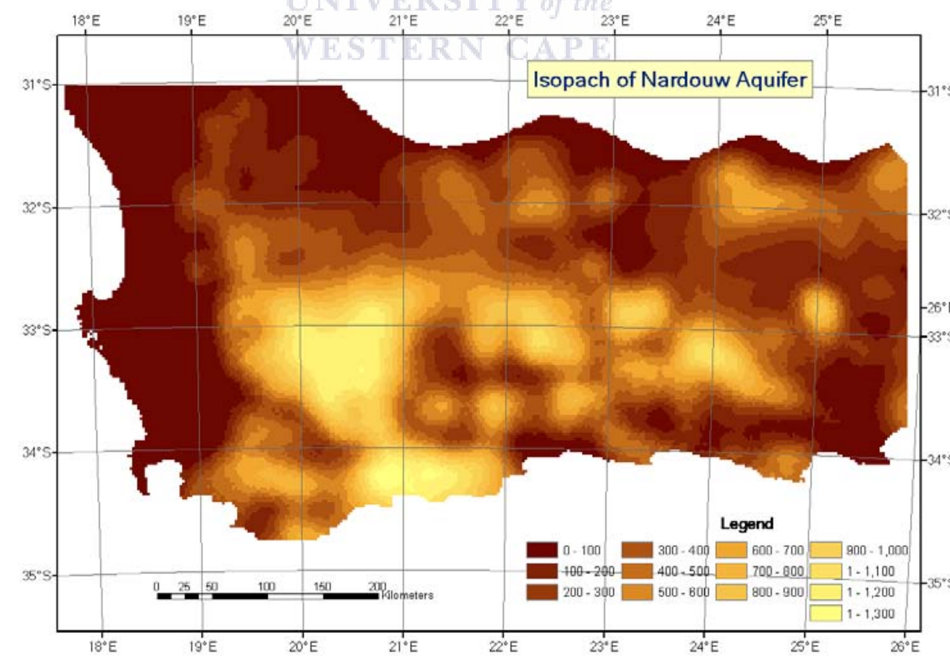


Fig. 4-29 Isopach of Nardouw Aquifer

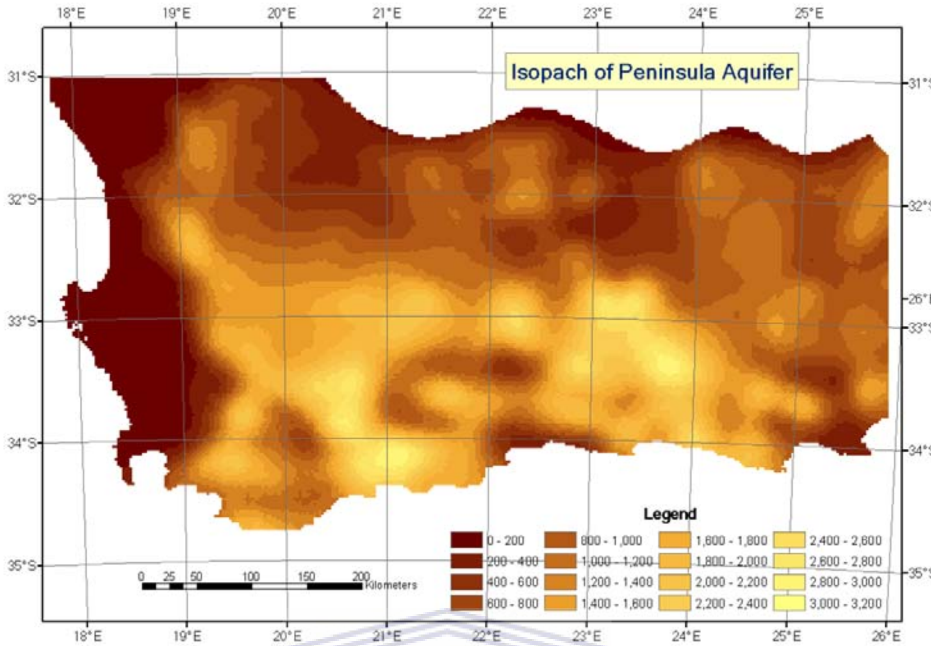


Fig. 4-30 Isopach of the Peninsula Aquifer

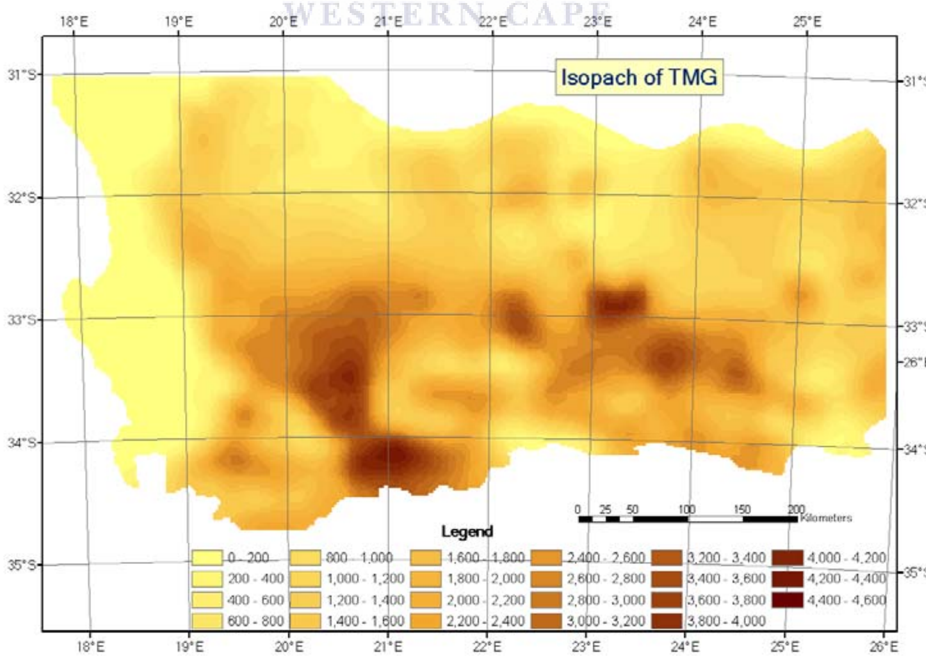


Fig. 4-31 Isopach of TMG Aquifer

4.5.3 Total groundwater storage capacity estimation

The total groundwater storage capacity (Fig. 4-17) is constant, which is dependent on the geometry and hydrogeological characteristics of the aquifer(s). Due to incomplete information about the groundwater storage properties, it is difficult to perform an accurately evaluation of total storage capacity in TMG auqifers. Also, total groundwater storage capacity may be misleading because it only considers one aspect of the physical character of the aquifers. Many other factors limit the ultimate development potential of a groundwater basin. These limiting factors could be physical, chemical, economic, environmental, legal, and institutional (CWR, 2003). Some of these factors, such as the economic and institutional ones, can change with time. In this section, based on the assumed specific yield and storage coefficient and the results of isobaths and isopachs derived in previous section, the total storage capacity is primarily calculated for 3 scenarios with high, medium, low storativity values. The estimation results are listed in Table 4-12.

Table 4-13 Estimation of total storage capacity of TMG aquifers

Unit: m^3, % of Aquifer Volume			**Outcrop (Unconfined)**		**Non-outcrop (Confined)**		**Total**	
Nardouw Aquifer	Aquifer Volume		6.4E+12		7.1E+13		7.8E+13	
	Total storage capacity	Low	4.5E+08	0.007%	5.0E+08	0.001%	9.5E+08	0.001%
		Medium	2.3E+09	0.036%	5.0E+09	0.007%	7.2E+09	0.009%
		High	2.3E+10	0.359%	5.0E+10	0.070%	7.2E +10	0.092%
Peninsula Aquifer	Aquifer Volume		1.8E+13		2.2E+14		2.4E+14	
	Total storage capacity	Low	6.4E+08	0.004%	2.2E+09	0.001%	2.9E+09	0.001%
		Medium	3.2E+09	0.018%	2.2E+10	0.010%	2.6E+10	0.011%
		High	3.2E+10	0.178%	2.2E+11	0.100%	2.6E+11	0.108%
Total	Aquifer Volume		2.4E+13		2.9E+14		3.2E+14	
	Total storage capacity	Low	1.1E+09	0.005%	2.7E+09	0.001%	3.8E+09	0.001%
		Medium	5.5E+09	0.023%	2.7E+10	0.009%	3.3E+10	0.010%
		High	5.5E+10	0.229%	2.7E+11	0.093%	3.3E+11	0.103%

4.5.4 Usable storage capacity estimation

Usable storage capacity (Fig. 4-17) is defined as the amount of groundwater of suitable quality that can be technically and economically extracted from the storage. It is computed by multiplying the average storativity of the aquifer by the volume of the aquifer to some specific depth that is considered technically and economically available. The usable storage may change because of changes in economic and technical conditions.

Estimates of usable storage simply represent the total volume of groundwater assumed to be usable in storage, but not what can be available for sustainable use on an annual basis and the limitations associated with total groundwater storage capacity discussed above may also apply to the estimation of usable storage.

In present study, considering the current situation of drilling techniques, the following limitations are set to be the limits of the usable storage capacity. First, the TMG aquifer storage capacity in Karoo area (which is located in the north part of study area) is excluded because boreholes have rarely touched the TMG rocks, which is considered to be deeply buried (>3000m below sea level). Second, 3 scenarios, 250m, 350m and 500m (below ground level), of drilling depth are applied to be the lower limit to calculate the useable storage capacity. The calculation results are listed in Table 4-13, Table 4-14 and Table 4-15 respectively.

Table 4-14 Estimation of usable storage capacity (500m below surface)

500m below surface Unit: m^3, % of Aquifer Volume			**Outcrop (Unconfined)**		**Non-outcrop (Confined)**		**Total**	
Nardouw Aquifer	Aquifer Volume		3.3E+12		6.0 E+12		9.2E+12	
	Usable storage capacity	Low	2.3E+08	0.007%	4.2E +07	0.001%	2.7E+08	0.003%
		Medium	1.1E+09	0.033%	4.2E +08	0.007%	1.6E+09	0.017%
		High	1.1E+10	0.333%	4.2E+09	0.070%	1.6E+10	0.174%
Peninsula Aquifer	Aquifer Volume		2.9E+12		3.7E +12		6.6E+12	
	Usable storage capacity	Low	2.9E+08	0.010%	3.7E +07	0.010%	3.3E+08	0.005%
		Medium	1.5E+09	0.052%	3.7E +08	0.052%	1.8E+09	0.027%
		High	1.5E+10	0.517%	3.7E+09	0.517%	1.8E+10	0.273%
Total	Aquifer Volume		6.2E+12		9.6E+12		1.5E+13	
	Usable storage capacity	Low	5.2E+08	0.008%	7.9E+07	0.001%	6.0E+08	0.004%
		Medium	2.6E+09	0.042%	7.9E+08	0.008%	3.4E+09	0.023%
		High	2.6E+10	0.419%	7.9E+09	0.082%	3.4E+10	0.227%

Table 4-15 Estimation of usable storage capacity (350m below surface)

350m below surface Unit: m^3, % of Aquifer Volume			Outcrop (Unconfined)		Non-outcrop (Confined)		Total	
Nardouw Aquifer	Aquifer Volume		2.4E+12		3.6E+12		6.0E+12	
	Usable storage capacity	Low	1.7E+08	0.007%	2.5E+07	0.001%	1.9E+08	0.003%
		Medium	8.3E+08	0.035%	2.5E+08	0.007%	1.1E+09	0.018%
		High	8.3E+09	0.346%	2.5E+09	0.069%	1.1E+10	0.183%
Peninsula Aquifer	Aquifer Volume		1.7E+12		1.8E +12		3.4E+12	
	Usable storage capacity	Low	1.7E+08	0.010%	1.8E +07	0.001%	1.9E+08	0.006%
		Medium	8.5E+08	0.050%	1.8E +08	0.010%	1.0E+09	0.029%
		High	8.5E+09	0.500%	1.8E+09	0.100%	1.0E+10	0.294%
Total	Aquifer Volume		4.1E+12		5.4E+12		9.4E+12	
	Usable storage capacity	Low	3.3E+08	0.008%	4.3E+07	0.001%	3.8E+08	0.004%
		Medium	1.7E+09	0.041%	4.3E+08	0.008%	2.1E+09	0.022%
		High	1.7E+10	0.415%	4.3E+09	0.080%	2.1E+10	0.223%

Table 4-16 Estimation of usable storage capacity (250m below surface)

250m below surface Unit: m^3, % of Aquifer Volume			Outcrop (Unconfined)		Non-outcrop (Confined)		Total	
Nardouw Aquifer	Aquifer Volume		1.7E+12		2.2E+12		3.9E+12	
	Usable storage capacity	Low	1.2E+08	0.007%	1.6E +07	0.001%	1.3E+08	0.003%
		Medium	5.8E+08	0.034%	1.6E +08	0.007%	7.4E+08	0.019%
		High	5.8E+09	0.341%	1.6E+09	0.073%	7.4E+09	0.190%
Peninsula Aquifer	Aquifer Volume		9.9E+11		8.9E +11		1.9E+12	
	Usable storage capacity	Low	9.9E+07	0.010%	8.9E +06	0.001%	1.1E+08	0.006%
		Medium	4.9E+08	0.049%	8.9E +07	0.010%	5.8E+08	0.031%
		High	4.9E+09	0.495%	8.9E+08	0.100%	5.8E+09	0.305%
Total	Aquifer Volume		2.6E+12		3.1E+12		5.8E+12	
	Usable storage capacity	Low	2.1E+08	0.008%	2.5E+07	0.001%	2.4E+08	0.004%
		Medium	1.1+09	0.042%	2.5E+08	0.008%	1.3E+09	0.022%
		High	1.1E+10	0.423%	2.5E+09	0.081%	1.3E+10	0.224%

4.5.5 Available storage capacity estimation

Available storage capacity (Fig. 4-17) is defined as the volume of an aquifer that is unsaturated and capable of storing additional groundwater. It is computed as the product of the empty volume of the aquifer and the average specific yield of the unsaturated part of the aquifer. The available storage will vary with the amount of groundwater taken out of storage and the recharge. The total groundwater in storage will change inversely as the available storage changes. Available storage has often been used as a number to represent the potential for additional yield from a particular basin. Unfortunately, many of the limitations that exist in developing existing supply discussed above also limit taking advantage of available storage. Although limitations exist, looking only at available groundwater storage capacity may underestimate the potential for groundwater development. Opportunities to use groundwater already in storage and create additional storage space would be overlooked by this approach.

In the present study, the unsaturated zone of TMG aquifer is assumed to be limited to the unconfined TMG area, where TMG rocks outcrop. There is no assured information for the determination of the elevation difference between the top of the aquifer and the potentiometric surface on a regional scale. Nevertheless Hartnady and Hay (2002) pointed out that it might be in the order of hundred meters over wide area. Consequently an elevation difference of 100m between the top of aquifer and the groundwater level is used to estimate the available storage capacity for the unconfined part of TMG aquifers. The estimation of available storage capacity of TMG aquifers is listed in Table 4-16.

Table 4-17 Estimation of available storage capacity of TMG aquifers

Unit: m^3, % of Aquifer Volume		Nardouw Aquifer		Peninsula Aquifer		Total	
Available storage capacity	Aquifer Volume	1.7E+12		2.2E+12		3.9E+12	
	Low	1.2E+08	0.007%	2.2E+07	0.001%	1.4E+08	0.004%
	Medium	5.8E+08	0.034%	2.2E+08	0.010%	8.1E+08	0.021%
	High	5.8E+09	0.341%	2.2E+09	0.100%	8.1E+09	0.208%

4.5.6 Storage capacity related to sea level

A significant part of groundwater in TMG aquifers may store below the sea level in the deep buried confined TMG aquifers. In this study, based on the results of isobaths and isopachs of TMG aquifers, the storage capacity related to sea level (above sea level and below sea level) is calculated using raster calculation function of the spatial analyst extension in ArcGIS. The calculation principal is illustrated in Table 4-17 with the example of Nardouw Aquifer. The storage capacity of Peninsula Aquifer related to sea level is estimated by the same way. The results are listed in Table 4-18. From Table 4-18 it can be observed that the estimated groundwater storage capacity below the sea level is about 5 to 10 times of it above the sea level.

Table 4-18 The calculation basis of TMG storage capacity related to sea level

Relationship between TopNar, BotNar and SL		Volume above sea level	Volume below sea level
TopNar is higher than SL	BotNar is higher or equal to SL	(TopNar-BotNar) * Grid Area	0
	BotNar is lower than SL	(TopNar-0) * Grid Area	(0-BotNar) * Grid Area
TopNar is lower or equal to SL		0	(TopNar-BotNar) * Grid Area

Note:

TopNar is elevation of the top of Nardouw Aquifer, BotNar is elevation of the bottom of Nardouw Aquifer, SL is sea level and Grid Area is the area of each grid of the raster file, i.e. 100 m × 100 m =10000 m^2.

Table 4-19 Estimation of storage capacity related to sea level

Unit: m^3, % of Aquifer Volume			Above sea level		Below sea level		Total	
Nardouw Aquifer	Aquifer Volume		1.1E+13		6.6E+13		7.7E+13	
	Groundwater storage capacity	Low	4.5E+08	0.004%	4.9E+08	0.001%	9.4E+08	0.001%
		Medium	2.2E+09	0.020%	4.9E+09	0.007%	7.2E+09	0.009%
		High	2.2E+10	0.200%	4.9E+10	0.074%	7.2E+10	0.094%
Peninsula Aquifer	Aquifer Volume		9.8E+12		2.3E+14		2.4E+14	
	Groundwater storage capacity	Low	5.9E+08	0.006%	2.4E+09	0.001%	3.0E+09	0.001%
		Medium	2.9E+09	0.030%	2.4E+10	0.010%	2.7E+10	0.011%
		High	2.9E+10	0.296%	2.3E+11	0.100%	2.6E+11	0.108%
Total	Aquifer Volume		2.0E+13		3.0E+14		3.2E+14	
	Groundwater storage capacity	Low	1.0E+09	0.005%	2.9E+09	0.001%	3.9E+09	0.001%
		Medium	5.2E+09	0.026%	2.9E+10	0.010%	3.4E+10	0.011%
		High	5.2E+10	0.260%	2.8E+11	0.093%	3.3E+11	0.103%

4.5.7 Change in storage

The definition of change in storage is as its name implies. The calculation of it can reflect the hydrologic trends in a groundwater basin or region over time. If change in storage is quite small over a specific period, the basin is in equilibrium under current condition. Groundwater budget is the most reliable way to estimate the change of storage, however it is usually limited by the availability and accuracy of data. An alternative and simpler way is to determine the average change in groundwater elevation over the study area or groundwater catchment, and then multiply the elevation change by the area and the average storativity. The choice of time interval of groundwater elevation change is study specific, but one-year cycle is usually adopted. Although the change in storage calculation is a relatively quick and inexpensive method of observing changes in the groundwater system, the full groundwater budget is preferable if data are available. Usually on a regional scale, the regional groundwater flow is assumed as steady-state where the change in storage could be taken as zero, which is the case in TMG aquifer systems.

4.6 Groundwater discharge estimation

Groundwater discharge of TMG aquifers includes natural discharge and exploitation. Natural groundwater discharge occurs through stream flow, spring flow, evaporation, leakage to the adjacent aquifer and discharge to the sea, the latter two of which are quite difficult to estimate in this study due to the insufficient subsurface geological information. The former four components of the natural groundwater discharge and the artificial exploitation discharge will be quantitatively estimated based on the existing data in this section.

4.6.1 Baseflow

It is well known that low-frequency baseflow can be separated from the stream flow by analyzing the stream hydrographs. However if or how much groundwater has contributed to the baseflow is still a question, though in a lot of documents baseflow is arbitrarily regarded as groundwater discharge to the stream flow. This issue will be detailedly discussed in Chapter 5. For a regional estimation, it is not realistic to clearly mark out groundwater discharge from the base flow. Nevertheless baseflow can be regarded as an upper limit of groundwater discharge from stream flow considering the occurrence of interflow and the possible hydrodynamic interaction between groundwater and the stream. One of the baseflow separation techniques, digital recursive filtering method, is applied to conduct the base flow estimation for TMG aquifers. Only the streamflow in outcrop areas are taken into account when calculating the total base flow issued TMG aquifers, while in the non-outcrop areas, because TMG aquifers are mostly deep buried, the stream flow is assumed to have no interaction with TMG aquifers but with the overlying layers, i.e. Bokkeveld Group.

The baseflow calculation result in Chapter 5 is used in this section, but the detailed procedures are not introduced here in this chapter. The total annual baseflow volume in TMG outcrop area is estimated as 1.08×10^9 m^3/yr.

4.6.2 Spring flow

As aforementioned, numerous springs issue from TMG, which is one of the characteristics of TMG area. Meyer (2002) has a detailed summarization and explanation of these springs. He generalized three types of springs related to TMG according to the mode of occurrence, including shallow circulating springs, lithology controlled springs and fault controlled springs. Because of the special hydrogeological significance of the fault-controlled springs, they are separated from the first two types and their contribution to groundwater discharge from TMG will be estimated separately. 501 springs can be identified with the depth of 0.01m in NGDB in TMG area, of which 103 are recognized as TMG-related springs according to their geographical relationship with TMG using the function of "Select by location…" in GIS. However with insufficient information they can't be classified into different occurrence types. The total yield of the 103 springs amounts to 141 *l*/s or 4.45×10^6 m^3/yr.

4.6.3 Hot spring

The notable 11 hot springs are unquestionably the discharge from the deep zone of TMG aquifers. The detailed information of these springs is listed in Table 4-7, in which the average yield of each is included. Therefore the total yield of these hot springs could be a good estimation of the deep zone discharge. The total yield of 11 hot springs is about 355 *l*/s or 1.12×10^7 m^3/yr.

4.6.4 Borehole yield

Borehole yield, or the exploitation discharge is usually the most concerned part of groundwater discharge of TMG aquifers. The estimation is made by summing up the discharge rate of the TMG-related boreholes. There are more than one records of discharge rate in many abstraction boreholes measured on different time, from which the latest one is used. The estimation results are listed in Table 4-19. The result shows that the biggest part of borehole yield is from the unconfined Nardouw Aquifer, i.e. 3139.76 *l/s* or 9.902×10^7 m^3/yr. The abstraction from the confined TMG aquifers only accounts for around 13.6% of the total abstraction, which reflects the situation that there are still technical limitations of drilling boreholes to the confined TMG aquifers

Table 4-20 Borehole yield estimation of TMG aquifers

Borehole Target Aquifer	**Nardouw Aquifer** *l/s* ($10^6 m^3$/yr)	**Peninsula Aquifer** *l/s* ($10^6 m^3$/yr)	**Piekenierskloof Aquifer** *l/s* ($10^6 m^3$/yr)	**Sum of TMG Aquifers** *l/s* ($10^6 m^3$/yr)
Unconfined	3139.76 (99.02)	1107.59 (34.93)	951.35 (30)	5198.7 (163.94)
Confined	686.37 (21.65)	130.47 (4.11)		816.84 (25.76)
Total	3826.13 (120.65)	1238.06 (39.04)	951.35 (30)	6015.54 (189.71)

4.7 Discussion on groundwater storage capacity and discharge in the TMG for water supply purpose

4.7.1 Demarcation of groundwater types in the TMG aquifers for water supply purpose

In the previous sections, the dynamic groundwater resource quantification of TMG aquifer systems is discussed and the related components such as groundwater recharge, storage and discharge are estimated using different approaches. These estimations are made by assuming the TMG aquifer as an independent groundwater system, which doesn't not take into consideration of the possible influence of other adjacent aquifers and the sea impact on TMG aquifers.

The concept of aquifer storage capacity is different from that of groundwater storage. On one hand, the storage capacity roughly provides a static insight into the TMG aquifers which may extend to a big depth. The estimated value ($3.3\times10^{10}m^3$) of the total TMG storage capacity for potential saturated zones is so big that it is about 30 times as the estimated precipitation recharge at a magnitude of $1.12\times10^9m^3$/yr. On the other hand, storage capacity does not necessarily equal to groundwater storage, which implies some of the potential aquifer space may not be occupied by groundwater. Therefore, it is often difficult to determine the size of the saturated zone especially in such fractured rock aquifers like the TMG.

The groundwater of the TMG aquifers mainly discharges as baseflow in stream flow, springs, hot springs and borehole yields. To a certain extent, these portions of water constitute valuable resources in the TMG area, and can be used by different groundwater users. Due to the specific spatial distribution of the TMG, the mechanism and quantity of groundwater discharges to the sea is unknown yet, but as discussed later the quantity of the TMG groundwater discharge to the sea is not as significant as the inland TMG groundwater.

With respect to the inland TMG groundwater, groundwater discharge to hot springs represents the part of water issuing from deep circulation, while groundwater discharge to streams, springs, and boreholes largely accounts for the water at relatively shallow circulation. So far there are not consistent criteria to demarcate groundwater at depth as deep and shallow flows, because the demarcation may greatly vary with the scale of problem studied. Even in a borehole scale, the deep and shallow flow zones can drastically change in the order of hundred meters, which depends on both the thickness and feasible technical approachs to the aquifer. In the case of TMG aquifers, the deepest circulation limit of groundwater perhaps can be represented by Brandvlei hot spring with a circulation depth of 3600m (Meyer, 2002).

From this perspective, the total storage capacity of $3.3\times10^{10}m^3$ in the TMG aquifers has been overestimated. In comparison with the deep groundwater, groundwater discharges to streams and boreholes constitutes the majority of shallow water. By considering the aquifer distribution and currently technical feasibility to exploit groundwater resources through boreholes in the TMG, the critical depth of 350m is taken as a limit of shallow flow. Accordingly, the aquifer storage capacity of the shallow zone is $1.29\times10^9m^3$, taking into account the capacity values in the zones above 350m and above 100m.

4.7.2 Groundwater discharge from TMG aquifers

Strictly speaking, the evapotranspiration is an important part of groundwater natural discharge in most cases. However, in the TMG area, the regional depth to groundwater table is conferred in the order of hundred meters (Hartnady and Hay, 2002), which gives little chance for discharge via evapotranspiration. Probably the presently estimated discharge items, i.e. baseflow, spring flow, hot spring and borehole yields, are not accurate enough, as the facticity of the estimation is highly dependent on the source data. However, the estimated results listed in Table 4-20 provide a quantitative insight into the component and magnitude of outflow ($1.29\times10^9m^3$/yr) of the TMG aquifers. These values are not fixed, but vary with the influence of climate (recharge by precipitation), human activities (development of more pumping wells), and other factors.

Other items that can't be properly estimated at this stage include leakage to the adjacent aquifers rather than TMG and groundwater discharge to the sea along the coast. About 211km coastline mainly distributed along the east and south coast has a direct contact with TMG outcrops. Assuming the precipitation within 300m of the coastline is able to be discharged to the sea, and the average recharge rate is 50mm/yr, equivalent to medium level of recharge estimation, the recharge volume is calculated at $3.17\times10^6m^3$, which approximates 1.67% of the total borehole yields as given in Table 4-20. Groundwater may also discharge to the sea through fracture networks at greater depths below the sea level; the quantification of this part of groundwater discharge is beyond the scope of this study.

Table 4-21 Discharge estimation of TMG aquifers

Items	Discharge rate (*l/s*)	Discharge rate (m^3/yr)
Base flow	34340.9	1.08E+09
Spring flow	141.0	4.45E+06
Hot spring flow	355.0	1.12E+07
Borehole yield	6015.5	1.90E+08
Discharge to the sea	101.0	3.17E+06
Sum	40953.4	1.29E+09

4.7.3 Groundwater budget on a regional scale

In the hydrologic cycle, groundwater is a renewable resource ultimately fed by precipitation. Meteoric water goes into aquifers as natural recharge and groundwater exits from them as natural discharge. The system can be assumed in a naturally steady state before development and recharge is balanced by natural discharge, i.e. evaporation, baseflow, springs, aquifer leakage, and so forth. When pumping process is imposed on an aquifer or aquifers, the natural balance is disturbed and it begins to evolve towards a new steady state. This state is achieved when the abstraction of the wells is balanced by the increased recharge, decreased natural discharge, or the combination of the two. The sum of the diverted discharge and induced recharge is called the "capture" of the wells. In a basin scale, the sustainable yield can be determined by the capture when no further withdrawals from aquifer storage are made and no unmanageable or intolerable effects have been created. Usually a groundwater budget is needed for the catchment management, which analyzes a groundwater catchment's inflows and outflows to determine the change in groundwater storage. Alternatively, if the change in storage is known, the value of one of the inflows or outflows could be determined. A detailed groundwater budget can provide understandings of the physical processes affecting storage in the catchment, which cannot be reflected in the simple calculation of change in storage. The basic equation of groundwater budget can be expressed as:

INFLOWS – OUTFLOWS = CHANGE IN STORAGE (4-7)

Inflows include:

- natural recharge from precipitation;
- seepage from surface water;
- human activities induced recharge;
- subsurface inflows from other catchment or aquifers.

Outflows include:

- discharge to surface water bodies and springs;
- extraction by wells;
- evapotranspiration; and
- subsurface outflow to other catchment or aquifers.

Groundwater budgets can be useful tools to understand a catchment and manage a catchment. A detailed groundwater budget requires subsurface exploration and monitoring over a series of years, the collection of field data is time-consuming and expensive. Consequently, detailed budgets are not available in most cases, especially on a regional scale like TMG area. A primary groundwater budget for TMG aquifer is shown in Table 4-21. Because this study is on a multi-year averaged basis, the item of change in storage is approximated as zero in the budget. Recharge by precipitation is the only item of inflows and others are ignored. With regard to the outflows, besides the baseflow item is estimated as the upper limit of groundwater discharge to streams, the evaporation loss, discharge to the sea and some other items of outflows are ignored, which may be evaluated in the future research. Most of the main components are included in the budget. The recharge quantity is about 1.12×10^9 m^3, which is considered to be balanced by 1.29×10^9 m^3 of the sum of outflows by taking into account the imprecision that may introduced by the data sources and the ignored items.

Table 4-22 Groundwater budget for TMG aquifer systems

Groundwater Budget	Items	Quantity (m^3/yr)
Inflows (Recharge)	Precipitation	4.4E+09 (Upper limit)
		1.12E+09 (Wu, 2005)
	Other sources	?
Outflows (Discharge)	Base flow (Upper limit)	1.08E+09
	Spring flow	4.45E+06
	Hot spring flow	1.12E+07
	Borehole yield	1.90E+08
	Discharge to the sea	3.17E+06
	Other sources	?
	Sum	1.29E+09
Change in storage		≈ 0

The accurate evaluation of sustainable yield for TMG aquifers could not be made presently from the existing knowledge and information, but some scenarios can be proposed. On a regional scale the sustainable yield can be determined by the long-term mean annual recharge or natural baseflow, as discussed in Chapter 2. According to the recharge estimation, together with the baseflow estimation in Table 4-20, a sustainable yield of no more than 1.0×10^9

m^3/year (or <35515 l/s) may be proposed for the groundwater exploitation of TMG aquifers. It can be seen that the present exploitation can be expanded to about 5 times current level with well-planned abstraction schemes. This is just an overall figure which doesn't necessarily mean that if the total abstraction from TMG aquifer is not higher than 1.0×10^9 m^3/year, there will be no inverse impact on the regional groundwater level or the environment. In other work, the exploitation must not be carried out in an arbitrary way. On specific site or local groundwater catchments, both the local groundwater-dependent ecosystems and the regional groundwater level should be cautiously considered before any inverse impact imposed by over-exploitation. What is also important is that the sustainable yield could not be regarded as a fixed value as it has a close relationship with the hydrodynamic system with the involvement of groundwater recharge and discharge, and can be adjusted on a seasonal basis according to the actual conditions within the limitation of a long-term scheme.

4.8 Groundwater quality of TMG aquifers

Generally speaking, TMG groundwater is of excellent quality with a very low salinity Na-Cl type due to the inert nature of the rock, mountainous terrain, and locally high rainfall. Bacteria and nitrate is seldom concentrated in the TMG groundwater except where the groundwater has been polluted by sewer system or other potential pollution source near the borehole. The electrical conductivity (EC) is usually less than 100 mS/m and most falls in the range of 20 to 50 mS/m, which makes the groundwater from TMG aquifer is suitable for most purposes. (Smart and Tredoux, 2002).

With regard to hydrochemical problems, corrosivity may arise from the softness, poor buffering capacity and acidic nature of the TMG groundwater. This problem can be avoided by considerate designs of water pumping and transportation equipment. Another problem is the presence of Ferrous iron, which is prevalent in the Nardouw Formation and also appears in the Peninsula Formation to a limited extent. It can result in problems like borehole clogging. The situation is more serious when associated with sulphate. So far the Fe occurrence is only partially understood. Research is needed to focus on the identifying of its formation processes and based on which, suitable prevention measures should be developed. The pollution of TMG groundwater is very limited at present, owing to the difficult access of the mountainous terrains that are usually nature reserve places. However, with the development of groundwater exploitation in future, cautions and measures should be taken in advance to ensure the quality of this precious resource in South Africa.

4.9 Summary

Though the TMG aquifers have been identified as a potential water supply for the Western Cape and Eastern Cape, the quantification or evaluation of the groundwater resources of such aquifers on a regional scale is still left blank excluding some rough estimates. Based on previous studies and existing data, the regional groundwater resource is initially assessed. According to the concept of groundwater resource expatiated in Chapter 2, the groundwater resource in the TMG aquifers are evaluated by recharge, storage and discharge.

Recharge is estimated using soil water balance approach. However the result can only be regarded as the upper limit of recharge, because the interflow in the TMG formations could not be successfully removed from the soil water surplus in the present model, which needs to be improved. The calculated total soil water surplus or the upper limit of recharge volume is about 4.36×10^{9} m^3 per annum, and the mean annual soil water surplus in TMG outcrop area is 115.38 mm, which is calibrated by the estimation by Wu (2005).

Groundwater storage capacity is classified into total storage capacity, usable storage capacity and available storage capacity and each of them is calculated based on the results of isobaths and isopachs of TMG aquifers and storativity value. The total groundwater storage capacity is estimated as 3.3×10^{10} m^3, which is roughly balanced by that of 5.2×10^{9} m^3 above sea level and 2.9×10^{10} m^3 below sea level. Considering current technical feasibility of groundwater exploitation in the TMG aquifer system, the usable storage capacity is evaluated with three scenarios presented by the exploitation depth of aquifers of 250m 350m and 500m, the amount of the storage capacity is 1.3×10^{9} m^3, 2.1×10^{9} m^3 and 3.4×10^{9} m^3 respectively. Available storage capacity is assumed as the storage capacity in the upper 100 m of the unconfined part of TMG aquifers and the amount of 8.1×10^{8} m^3 is yielded. In term of water supply, the TMG groundwater is demarcated as deep flow and shallow flow. The former is basically represented by hot springs with a deepest circulation of 3600m in the TMG area. The later is defined as the zone between 100 and 350m below surface, in which the storage capacity is 1.29×10^{9} m^3.

Groundwater discharge from TMG aquifers through baseflow, springs, hot springs, abstractions, and to the sea is evaluated with the sum of 1.3×10^{9} m^3/yr, in which the estimate of baseflow (1.1×10^{9} m^3) represents an upper limit of groundwater discharge to streams, whilst the others account for 2.1×10^{8} m^3 of groundwater discharge. The groundwater discharge to the sea above sea level is roughly estimated with the existing data, but the discharge to the sea below the sea level is known yet.

A primary groundwater budget is carried out and it is considered that the inflows and outflows are balanced with the consideration of possible imprecision. A sustainable yield of no more than 1.0×10^{9} m^{3}/year (or <35515 l/s) is proposed for the groundwater exploitation of TMG aquifers based on the groundwater budget. The existing exploitation could be expanded properly.

Generally the TMG groundwater is of excellent quality and is suitable for all purposes. The problems mainly includes corrosivity and Ferrous iron, which needs to be investigated on the formation processes and suitable prevention measures. Pollution in TMG groundwater is very limited at present but may be a threat with the development of groundwater exploitation.

5. Groundwater & surface water interaction of TMG aquifers

——Focused on baseflow analysis

5.1 Introduction

In recent years, with the implementation of new legislation on water resource in South Africa, more emphases are placed on the protection of water resources for their sustainable utilization. A new term, ecological reserve, is proposed to represent flow requirements for aquatic ecosystems. Another term instream flow requirement (IFR) is adopted to stand for the ecological reserve in the streams, which can also be regarded as groundwater discharge or baseflow. A quantified study on groundwater and surface water interaction (GW-SW interaction) in the context of streams is required for the determination of baseflow proportion in the stream, after which a proper water allocation could be carried out without causing any negative impact on the groundwater dependent ecosystems (Xu et al, 2002).

The GW-SW interaction is controlled by the positions of the surface water bodies relative to the groundwater levels, the characteristics of their beds and underlying materials, and their climatic setting (Winter et al., 1998). The geologic settings of the groundwater and surface water interface may affect the groundwater flow path, and the sediments type of the interface can also cause the spatial variability of groundwater discharge to surface water and in turn, affects the distribution of the related ecosystem. Water exchange across the surface water – groundwater interface has been explored in some detail in the past decade, with most studies focused on streams (Jones and Mulholland, 2000). The interactions of groundwater with lakes, wetlands, estuaries, and oceans are also recognized as important processes (Mortimer et al., 1999; Fraser et al., 2001; Moore, 1999; Basu et al., 2001).

Knezek and Krasny (1990) stated that groundwater runoff or baseflow assessment is the best way to estimate regional groundwater resources. With regard to resource evaluation, GW-SW interaction could be quantified in dual sides. On one hand groundwater obtains recharge from surface water, i.e. losing streams or river leakage. On the other hand, groundwater can discharge to surface water, i.e. stream baseflow (Lerner, 2005). Generally, the proper identification and quantification of the interaction can help to improve the facticity and precision of groundwater resource evaluation. The interaction between groundwater and stream is ubiquitous in TMG outcrop areas, especially in the regions where large-scale groundwater exploitation has not started and the natural hydrological balance is dominated.

The picture depicted in Fig. 5-1 is taken from a ready-to-develop groundwater supplying site in TMG outcrop area. The bedrock is Nardouw Formation. The stream is perennial, which implies its source could come from both the rapid surface runoff and more stable groundwater discharge from TMG aquifer. The stream flows into a mountainous lake, the leakage of which could be the recharge source of the lower lying TMG aquifers.

Fig. 5-1 The G/S interaction in TMG outcrop area

In this chapter the basic concepts of groundwater and surface water interaction are simply introduced and then the groundwater and surface water interaction related to TMG aquifers is studied focusing on stream baseflow analysis, from which the value of mean annual baseflow is estimated as one component of the groundwater discharge from TMG aquifers.

5.2 Basic concepts of groundwater and surface water interaction

It is well understood that groundwater and surface water are fundamentally interconnected. GW-SW interaction may occur at various zones in the hydrological cycle. As rain or snow (precipitation) falls to the earth's surface, some water may enter the soil and infiltrate deeper to reach groundwater. When the groundwater level is higher than the surface water stage, groundwater will discharge to the surface water through wells, springs and marshes and becomes surface water.

The United States Geological Survey (Winter et al., 1998) has described a conceptual landscape to define the most common types of groundwater and surface water interaction. The following types of terrain are defined: mountainous river valleys, coastal, glacial and dune, and karst. Descriptions of typical interactions are presented in Winter et al., 1998. A simple introduction of the mountains terrain and river valleys is quoted here.

In mountainous terrains, usually in the inter-storm or snowmelt periods, mountainous streams are sustained by groundwater discharge from the adjacent aquifer, whereas during the storms the surface runoff quickly flows to the streams. Fig. 5-2 shows the interaction type of groundwater and surface water in mountainous terrain. Basically the mountainous stream flow is composed of overland flow on the hill slope, interflow from the unsaturated zone and groundwater discharge from the groundwater storage. Their respective proportions are depending on the climatic and geologic factors.

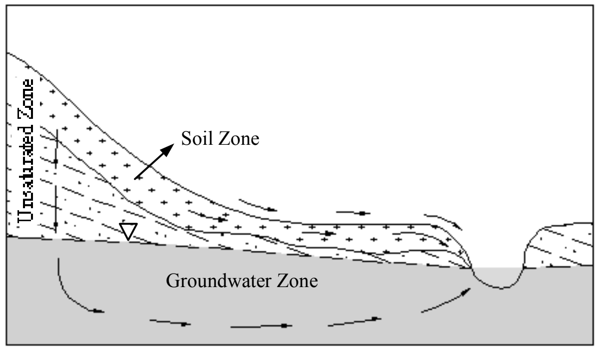


Fig. 5-2 Groundwater and surface water interaction in Mountains terrain (after Winter et al., 1998)

In a river valley terrain, the extent of interaction between groundwater and surface water in river valleys depends on the scale of the river. Similar to the mountainous terrain, climatic factors, i.e. storm induced flooding and evapotranspiration, and geologic factors, i.e. the riverbed deposits, also play a role in the process of water exchange in river valley terrain. As expected, small streams usually receive groundwater discharge from local flow systems, which are limited and highly seasonal and appear to be intermittent streams. As to large river valleys or flood plains, groundwater discharge from regional flow systems may flow to the river or the flood plain. The occurrence of fault lines may also create areas where significant exchanges between surface water and groundwater occur. Fig. 5-3 shows the interaction type of groundwater and surface water in river valley terrain.

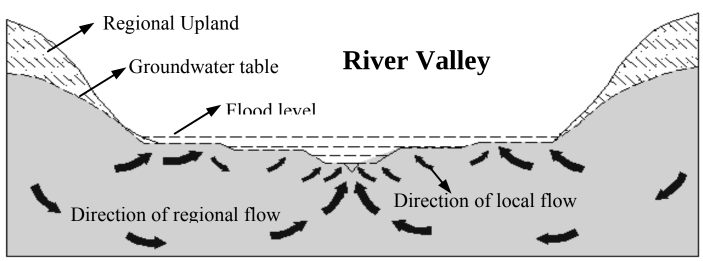


Fig. 5-3 Groundwater and surface water interaction in River Valley terrain (after Winter et al., 1998)

In South Africa, especially in TMG area, GW-SW interaction occurs within the streams more than other surface water bodies like lakes, wetlands, and etc. The interaction between groundwater and streams depends on their relative water levels, by which four basic types of streams are identified according to the relative elevation of the water level in the stream to that of the water table of the groundwater. The four types of streams are described as follows.

1) Gaining streams: Streams gain water from groundwater through the streambed when the groundwater table adjacent to the streambed is greater than the water level in the stream.

2) Losing streams: Streams lose water to groundwater by outflow through the streambed when the elevation of the water table is lower than the water level in the stream.

3) Detached streams: For some streams in more arid region, the GW-SW interaction becomes quite inactive. The vadose zone exists between the riverbed and the groundwater body. The stream may only flows after heavy rains. Some time after the storm, water in the stream may seep into the subsurface and reach the groundwater, acting like a losing stream. Whereas when the flow stops the seepage is also ceased.

4) Intermittent streams: In some instances a stream may take on different characteristics during different seasons. Usually in wet season or flood season, the water table rises up to the base of the stream and the characteristic of the stream can range from a detached stream to a gaining stream. After the wet season, as the water table declines, the stream may attain a losing character before reverting back to a detached stream.

The quantification of GW-SW interaction in streams has been studied using different approaches for specific sites, quaternary catchments or a single hydrological event (Smakhtin, 2001; Linsley et al., 1958; Farvolden, 1964; Rorabaugh, 1964; Halford and Mayer, 2000 Rutledge, 1993; Mayer and Jones, 1996). Based on hydrogeomorphological understanding, Xu et al (2002) propose an empirical approach to estimate the IFRs, which combines both the hydrogeomorphological typing of the streams and the quantitative separation and makes the estimation more realistic. However for a regional study like TMG area, it is impossible to investigate each individual stream for the right typing and assign the most reasonable quantification algorithm to derive the groundwater discharge proportion in the streams. Some empirical methods could only be applied to perform the estimation in a batch-calculation way. Different parameters could be set to allow for the different hydrogeological and hydrometeorological settings of the streams.

5.3 The interaction between groundwater and streams related to TMG aquifers

From the result of groundwater discharge estimation in the previous chapter, it is clear that the baseflow, which is assumed to be the upper limit of the groundwater discharge to stream flow, accounts for the largest proportion of the existing estimable groundwater discharge components. It is estimated that there is at most 1.1-billion m^3groundwater discharge to streamflow from the TMG aquifers each year, which is a huge quantity and questionable. A further discussion on this will be made in this section.

5.3.1 Periodicity of streamflow and long-term trend

5.3.1.1 General climate change and periodicity of streamflow in South Africa

Flow in streams is not invariable for the whole year. It may have a quick response to a short rainfall event as we usually can see directly. Besides, what gets more attention of the hydrologists is the seasonality of the stream flow under the seasonal climate variations. Expand the view to a long history of the streamflow, it also can be found that the medium-term cycle or long-term trend which spans longer period than one-year fluctuation also exist. The variation of the stream flow has a close relationship with the climate change.

Meyer (2005) has made a comprehensive review on the issue of climate change in Southern Africa. The ancient climate (during the Pleistocene and Holocene) cycles and the climatic variations during the last 200 years are summarized in his report. The major wet and dry phases in the Kalahari are listed in Table 5-1.

In Meyer's report (Meyer, 2005), it is stated that various cyclic rainfall oscillations have been noted from the perspective of groundwater in South Africa, including 18-years, 10.5-years and also the smaller amplitudes at 3.5 or 2.3 years. Moreover, R Meyer quoted many researchers' results to confirm that there is no evidence to support the idea that South African rainfall is undergoing a general long-period decline.

5.3.1.2 TMG-related rainfall zones and streamflow gauge stations

In WR90 (Midgley et al., 1994), 448 rainfall zones are demarcated throughout the country, and the representative rainfall histories were compiled for each zone. The rainfall zones are built up by congregating quaternary catchments having similar rainfall characteristics. By implementing the selection function in GIS, the TMG outcrop areas are located in 83 rainfall zones, in some of which only very tiny TMG outcrop areas appear.

Only 17 streamflow gauge stations with monthly flow records are identified in TMG outcrop areas with the intention of studying the baseflow characteristics related to TMG. A further filtering has been carried out to these gauge stations by overlying river and TMG outcrop maps on the gauge-station location map to check what kind of hydraulic relationship between the streams and TMG aquifers. The GIS analysis shows that 13 of these gauge stations have full relationship with TMG because the gauged part of the streams is almost entirely located on TMG outcrop areas. 3 of the stations are identified to be half related to TMG aquifers with only part of the gauged reaches located on TMG outcrop areas. 1 station is found that has no hydraulic relationship with TMG at all and is left out of the study. The types of the gauged streams (Perennial or Non-Perennial) are also available from the associated attributes of the stream map and they can also be calibrated with the rainfall records on these gauge stations. Fortunately the spatial distribution of the 16 TMG-related gauge stations (Fig. 5-4) is almost throughout the whole TMG area and could be representative. The rainfall records of the corresponding 14 rainfall zones in which these gauges are located are also extracted from the database to work in with the stream flow data. Table 5-2 lists the basic information on these gauge stations.

Table 5-1 Major wet and dry phases in the Kalahari during the 19th century and for South Africa in general for the 20th century. (After Meyer, 2005)

Major wet periods	Major drought periods	Probable regional extent
1816/17		Southern Kalahari
	1820-1822	Cape. Dry period of below normal rainfall.
	1820-1827	Southern Kalahari plus parts of the former Eastern Cape*
1829/1830		Southern Kalahari plus adjacent parts of South Africa*
	1831-1835	Southern Kalahari plus parts of the former Eastern Cape*
	1844-1851	Entire Kalahari plus adjacent parts of Angola and Zambia*
1851/52		Entire Kalahari plus large areas of South Africa
	1857-1865	Middle and Southern Kalahari plus much of South Africa, with drought punctuated by widespread wetter conditions in 1863/64*
1863/64		Southern Kalahari plus areas of former Eastern Cape
1874/75		Middle and Southern Kalahari plus large areas of South Africa*
	1877-1886	Entire Kalahari plus parts of South Africa
1889-1991		Middle and Southern Kalahari plus large areas of South Africa*
	1894-1899	Entire Kalahari plus large areas of neighbouring South Africa
1899/1900		Middle and Southern Kalahari plus adjacent parts of South Africa
	1905/06-1915/16	Southern Africa
1916/17-1924/25		Southern Africa
	1925/26-1932/33	Southern Africa
1933/34-1943/44		Southern Africa
	1944/45-1952/53	Southern Africa
1953/54-1961/62		Southern Africa
	1962/63-1970/71	Southern Africa
1971/72-1980/81		Southern Africa
	1982/83-1992/93	Southern Africa
1993/94-2002/3		Southern Africa*

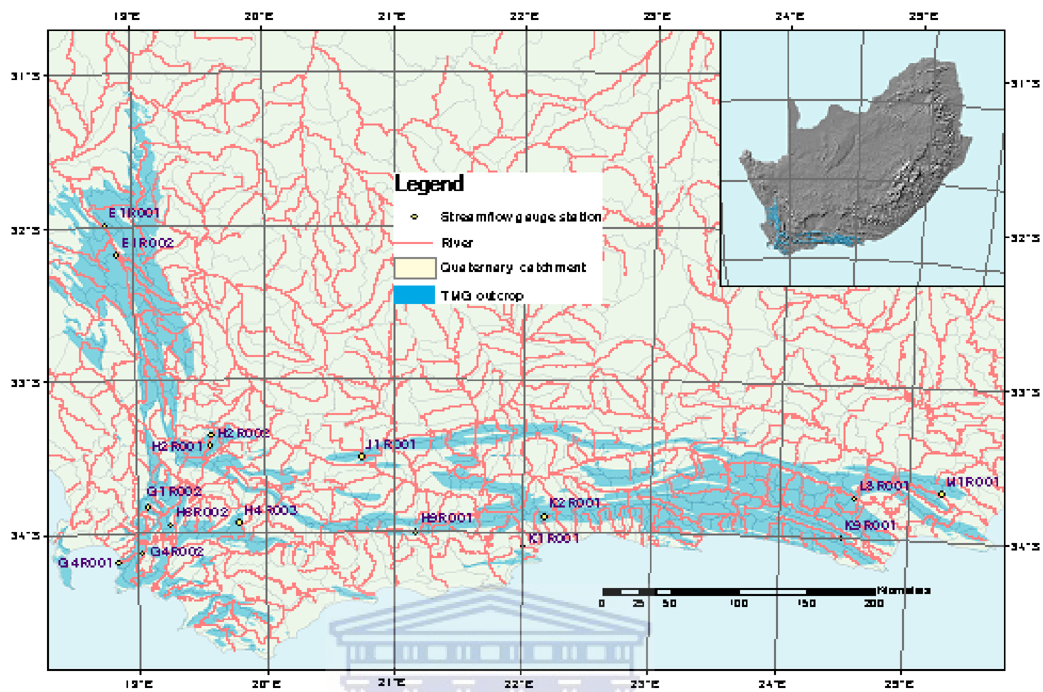


Fig. 5-4 The spatial distribution of TMG-related river flow gauge station with data records

Table 5-2 The information of streamflow gauging stations in TMG outcrop areas

Station No.	Rainfall zone	MAP (mm)	Gauged area (km^2)	Gauged QCat(s)	MAR (Mm^3)
E1R001	E1D	250	2769	E10A-E10J & Part of E10K	396.1
E1R002	E1C	350	2033	E10A-E10G	395.8
H2R001	H2	600	139	H20C & Part of H20D	19.5
H2R002	H2	600	80	H20C	5.5
G1R002	G1A	1000	86.2	Part of G10B	69.3
G4R001	G4C	900	66.8	Part of G40A	43.8
G4R002	G4C	900	63	Part of G40C	54.7
L8R001	L8D	400	3887	L81A-L81D & L82A-L82H	187.1
K9R001	K9B	700	357	K90A-K90B	53.4
K1R001	K1	400	100	Part of K10B	2.4
K2R001	K3	700	16.8	Part of K20A	3.7
H4R003	H4C	400	54	Part of H40K	2.8
H6R002	H6A	1000	50	Part of H60C	23.9
J1R001	J1D	300	757	J12G	3.5
H9R001	H8A	600	37	Part of H90B	9.5
M1R001	M1A	600	265	M10A	16.0

Table 5-2 The information of streamflow gauging stations in TMG outcrop areas (Continue.)

Station No.	Gauged River	River Type	Hydraulic relation type with TMG	Record period	Data facility
E1R001	Olifants	Perennial	Fully	1933-1988	Good
E1R002	Olifants	Perennial	Fully	1935-1989	Good
H2R001	Sanddrifskloof	Non-Perennial	Fully	1967-1986	Medium
H2R002	Sanddrifskloof	Non-Perennial	Fully	1970-1987	Medium
G1R002	Wemmers	Perennial	Fully	1956-1988	Medium
G4R001	Steenbras	Perennial	Fully	1921-1987	Good
G4R002	Palmiet	Perennial	Fully	1978-1988	Poor
L8R001	Kouga	Perennial	Fully	1961-1989	Medium
K9R001	Kromriver Dam	Non-Perennial	Fully	1948-1988	Good
K1R001	Kartenbos	Non-Perennial	Partly	1970-1988	Medium
K2R001	Groot Brak	Perennial	Fully	1965-1974	Poor
H4R003	Konings	Non-Perennial	Fully	1966-1989	Medium
H6R002	Elands	Perennial	Fully	1981-1988	Poor
J1R001	Prins	Non-Perennial	Partly	1920-1977	Good
H9R001	Korinte	Perennial	Partly	1967-1989	Medium
M1R001	Swartkops	Perennial	Fully	1938-1988	Good

5.3.1.3 Long-period trends of rainfall and streamflow in TMG outcrop areas

To indicate the condition of climatic cycles in TMG area, the rainfall history expressed by a spatially-averaged percentage of annual rainfall of the abovementioned 15 rainfall zones from 1920 to 1989 and the relevant smoothed rainfall (averaged by 5 years continuously) are depicted by Fig. 5-5. It is difficult to recognize the abovementioned wet or dry periods from the chart probably because less statistic techniques are used to summarize the cycle. However it's clear that the rainfall periodicity does exist. Otherwise it can be confirmed from the linear trend line of the spatially averaged rainfall that the rainfall in this area was not undergoing a long-period decline. On the contrary it shows a slight incline (Slope K=0.0941) with time going on.

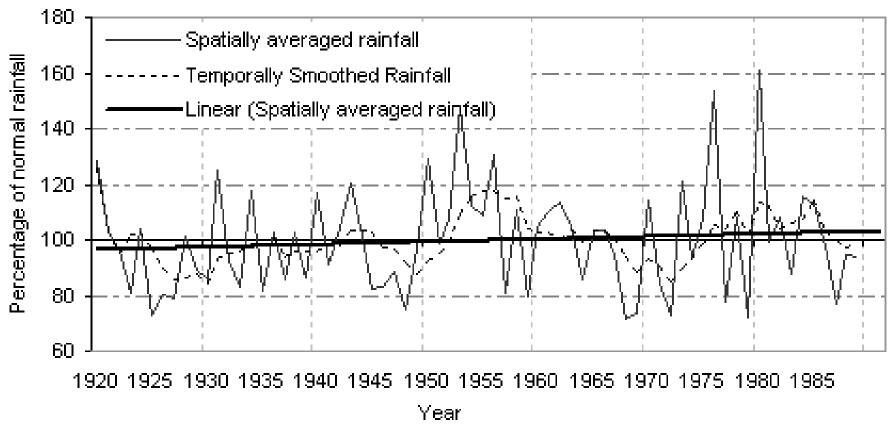


Fig. 5-5 Spatially averaged rainfall and temporally smoothed rainfall in TMG outcrop area

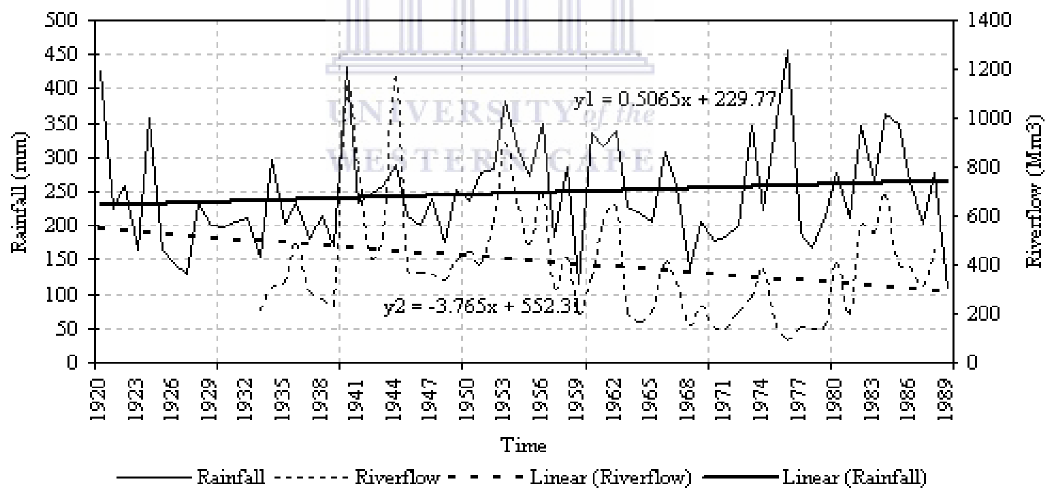


Fig. 5-7 Annual rainfall and riverflow records and their trendlines of riverflow gauge station E1R001

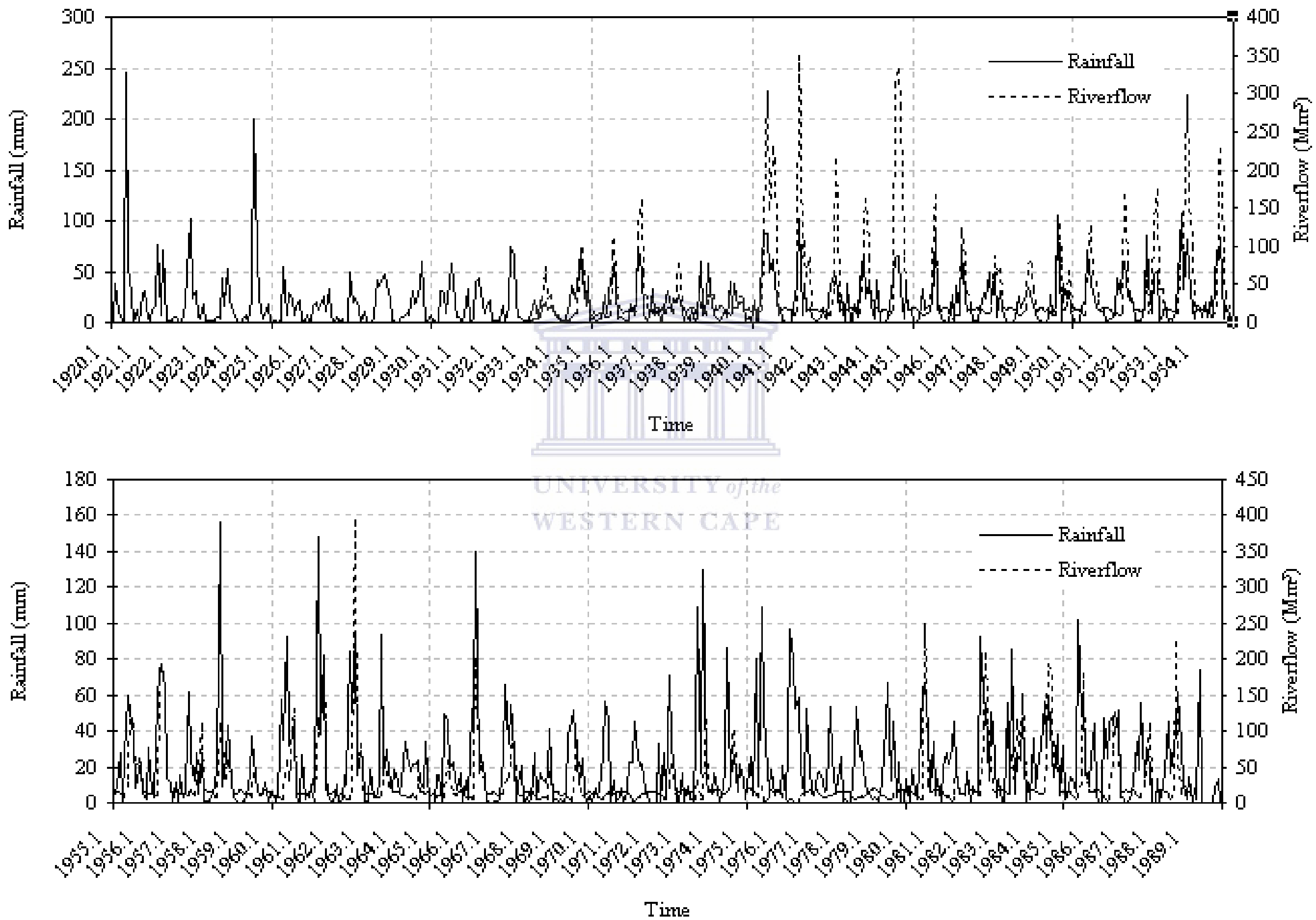


Fig. 5-6 Monthly streamflow and rainfall records from 1920 to 1989 on station E1R001

As aforementioned, the streamflow variations are mainly attributed to the climate changes. The hydrograph of a specific streamflow gauge station usually has the identical oscillations with that of the rainfall on the same site. The monthly streamflow records and rainfall records from 1920 to 1989 for station E1R001 is plotted in Fig. 5-6 to depict the phenomena. Thereby the study of the periodicity of the rainfall could be applied to the streamflow in most cases. Alexander (1995, 2002) analyzed South African stream flow data and confirmed a 19 to 21 year periodicity in both rainfall and stream flow records. The annual rainfall and streamflow records of the 16 streamflow gauge stations located in TMG outcrop areas from 1920 to 1989 are analyzed by charts and the chart of E1R001 is showed by Fig. 5-7 as an example. Some or part of the streamflow data is missing and then left blank. The relationships between the rainfall and streamflow are presented explicitly and both of their linear trendlines are added to the charts intending to illustrate their respective long-period direction of incline or decline, which are also summarized for each streamflow gauge in Table 5-3.

Table 5-3 Summary of long-period trends of rainfall and streamflow for 16 streamflow gauge stations in TMG outcrop

Station No.	Rainfall		Streamflow		Region
	Trend	Slope (k)	Trend	Slope (k)	
E1R001	Inc.	0.5065	Dec.	-3.765	West
E1R002	Inc.	1.1102	Dec.	-1.9074	West
G1R002	Inc.	1.2861	Dec.	-0.2722	West
G4R001	Inc.	1.8289	Dec.	-0.1784	West
G4R002	Inc.	1.8289	Dec.	-0.1771	West
H4R003	Inc.	0.5585	Dec.	-0.454	West
J1R001	Inc.	0.1675	Dec.	-0.0361	West
H2R001	Inc.	2.0226	Inc.	0.4932	Middle
H2R002	Inc.	2.0226	Inc.	0.095	Middle
H6R002	Inc.	0.8843	Inc.	1.2175	Middle
H9R001	Inc.	1.1384	Inc.	0.1687	Middle
K1R001	Inc.	1.0768	Inc.	0.0649	Middle
L8R001	Dec.	-1.1995	Dec.	-1.1842	East
K9R001	Dec.	-1.3838	Dec.	-0.8023	East
K2R001	Dec.	-0.0524	Inc.	0.0009	Middle
M1R001	Dec.	-0.1559	Inc.	0.0626	East
*Inc. Incline, Dec. Decline					

Table 5-3 lists the long-period trend of rainfall and streamflow for the 16 streamflow gauge stations together with the linear slope k derived from the chart. An evaluation with three rankings of “Good”, “Medium” and “Poor” on the streamflow data facticity is performed based on the length and the natural continuity of the records. Most of the data are ranked as “Good” and “Medium” whist only 3 of them are ranked as “Poor” due to the < 10 years’ record length. The relative location of each gauge in TMG area is also listed in the table to indicate the locality of rainfall and streamflow pattern. It can be observed that in the west and middle region of the TMG outcrop areas, where the winter rainfall pattern prevails, the long-period trend of rainfall shows a slight incline. In the east region where an averaged annual rainfall pattern prevails, the rainfall was undergoing a progressive decline. Furthermore, in the winter rainfall region, with the long-period increase of rainfall, the streamflow presents two different trends with locality characteristics. In the west region of TMG outcrop area, the streamflow shows a progressive decline, though with the increase of rainfall. In the middle region, however, the streamflow increased as well as the rainfall. A reasonable explanation to this phenomenon may be that there was more groundwater abstraction in the west region of TMG area than the middle region during the study period. From Fig. 4-8 (distribution map of TMG-related boreholes), it can be easily seen that the distribution of the boreholes in the west region is much denser than that in the middle region. In order to eliminate the inference of the boreholes that were constructed after 1989, they are filtered by the construction time using the database query function in GIS. The result shows that about 10%-15% of these TMG-related boreholes were constructed after 1989, which means they can hardly bias the abovementioned analysis. In the east region, though two of the records show an incline trend of streamflow, one of them is derived by poor streamflow data records and the other one just increases with a slight slope (k=0.0626). It is inferred that the long-term streamflow was undergoing the progressive decline with the same rainfall trend and the influence of groundwater abstraction.

5.3.2 Baseflow

5.3.2.1 Stream hydrographs

A stream hydrograph (Fig. 5-8) is made up of several components, which normally include direct precipitation, overland flow (surface runoff), and baseflow (both interflow and groundwater discharge). The concept of baseflow is differently understood by hydrologists and hydrogeologists (Chapman, 1999). Surface hydrologists usually identify baseflow as the low amplitude and high frequency flow events, and based on which, baseflow separation techniques are used to separate the baseflow component from the stream hydrograph. However, the origins and the mechanisms of the generation of water are seldom

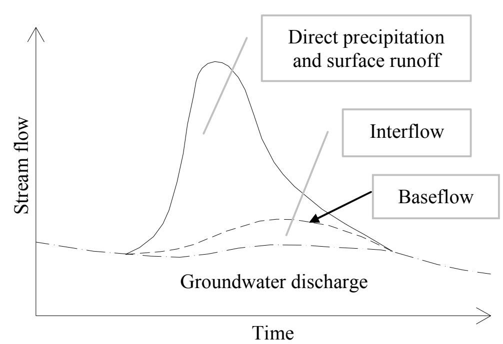


Fig. 5-8 Typical streamflow hydrograph

concerned or involved in their techniques. On the other side, the hydrogeologists often take baseflow as the groundwater contribution to the stream and it provides an approach to estimate the related recharge, discharge and dynamic storage of groundwater.

5.3.2.2 Baseflow separation

Many of the hydrograph separation approaches are trying to distinguish between rapidly occurring overland flow, slower moving interflow and even slower groundwater discharge from the stream hydrographs (Freeze, 1972a). However the interflow component is not easy to marked out quantitatively and usually can only be illustratively depicted on the graph. In some cases the interflow component is overlooked to simplify the separation process. Freeze (1972b) concluded that the overland flow can become a quantitatively significant streamflow component only on convex hill slopes that feed deeply incised channels, and only when the permeability of the soils on the hillslope is in the very high bracket of the feasible range. Generally the fact is that the separated baseflow cannot be arbitrarily regarded as the groundwater discharge but the upper limit of it, especially in the mountainous catchments. A lot of separation techniques have been reviewed (Nathan et al., 1990; Tallaksen, 1995; Boughton, 1998; Xu et al., 2002; Eckhardt, 2004). These methods can generally be summarized into two groups, viz. "event-based separation methods" and "continuous separation techniques" (Smakhtin, 2001).

Event-based baseflow separation methods

Usually the event-based separation methods focus on separating baseflow from a flood hydrograph and are eventually aimed at the estimation of surface runoff component of flood. In most of the literatures the flood event is regarded as single rainfall event. However, it could be a hydrologic event of various magnitudes to meet different study needs. For example, a quick response of streamflow to instantaneous rainfall may be studied on a daily or an hourly scale, while for the unevenly distributed monthly stream hydrograph, stormflow or surface runoff dominate the streamflow and high discharge months may also be characterised by hydrological event in a broad sense.

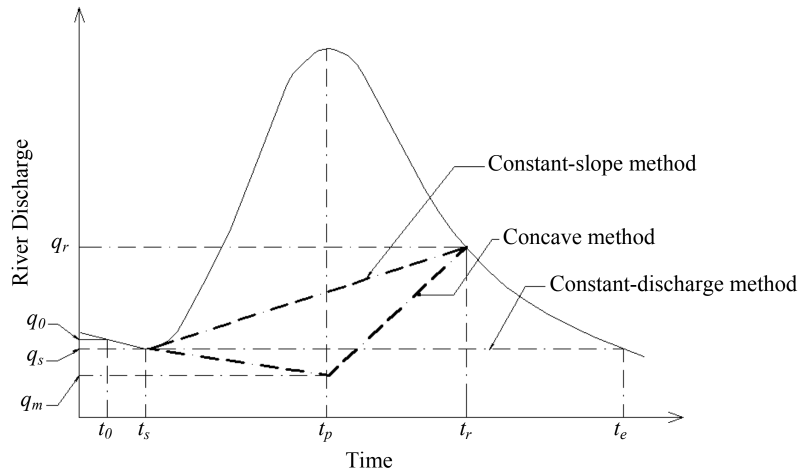


Fig. 5-9 Event-based baseflow separation methods (after McCuen, 2004)

The event-based separation methods are generalized by McCuen (2004) and shown in Fig. 5-9:

- *Constant-discharge* – start at beginning of rising limb of the hydrograph, draw horizontal line until it intersects recession curve. This is based on the assumption that the baseflow remains constant. It is easy to manipulate, but baseflow should increase following a storm event.
- *Constant-slope* – start at beginning of rising limb, draw an upward sloping line to the inflection point on the recession limb. It should be noted that the inflection point on the recession limb is taken to be the end of surface runoff and the time from the end of rainfall to the inflection point is the watershed "time of concentration". The problem is that it can be difficult to exactly determine the inflection because of the noisiness of field data. A widely used empirical relationships can be applied to determine the inflection point: $T = A^{0.2}$, where T is days from peak to inflection point, and *A* is basin area in mi^2.
- *Concave* – extend the pre-storm recession trend (linearly) until the time of peak (tp), then draw an upward sloping line to the inflection point.

Continuous baseflow separation method

The continuous separation method is designed to distinguish baseflow components from stream hydrograph for a longer period, for instance one year or several years, or the entire period of observations. The purpose of continuous separation techniques is that the baseflow characteristics may provide a qualitative or quantitative understanding of the interaction between groundwater and streamflow. The easiest method of this type of techniques is the “local minimum method”, which mainly deals with the daily streamflow data. Other methods of continuous separation techniques are mostly digital filter methods. Normally a filtering procedure is employed to disintegrate the streamflow time series into quick flow and baseflow. Quite a few digital filter methods and their applications have been reported, including the BFLOW filter (Lyne and Hollick, 1979), Eckhardt filter (Eckhardt, 2004), smoothed minima method (FREND, 1989), recursive digital filter (Nathan and Mcmahon, 1990) and a lot of others (Sittner et al., 1969; Birtles, 1978; Boughton, 1988; Smakhtin, 1993; Sloto, 1996). Another notable method in this category is the hydrogeomorphological approach to the quantification of groundwater discharge to streams proposed by Xu et al. (2002). His work is based on a geomorphologic framework. The hydrogeomorphological typing is used to guide a process of separating groundwater discharge time series from hydrographs. Generally speaking, contrary to the event-based baseflow separation methods, all the continuous baseflow separation techniques do not focus on simulating baseflow conditions for a particular hydrologic event but the quantitative estimation of long-term baseflow response of a catchment.

Considering the characteristics of this study, it is not realistic to apply the event-based baseflow separation method on a regional-scale. Among the continuous baseflow separation methods, the local minimum method is more suitable for the daily flow data. As the stream flow data are stored on monthly basis in WR90, finally the recursive digital filter method is selected to be adopted in this study because of both the availability of data and the successful experience of applying this method in South Africa (Smakhtin, 2001; Hughes et al., 2003).

Recursive digital filter method and its application in TMG outcrop areas

Both the daily and monthly streamflow time series are appropriate for baseflow separation, whilst the former simulates the baseflow response on a more detailed basis better. Daily data series are not always available or are cumbersome to deal with even when available. In South Africa, all the streamflow data have been arranged in monthly series on a regional scale. Therefore a preferable technique for monthly baseflow separation is required. One of the abovementioned continuous baseflow separation techniques, recursive digital filter method, is then selected in this study. It originates from signal analysis and was first used in hydrology by Nathan et al. (1990). This method has been widely used to the monthly streamflow data for South African streams and catchments and yields satisfactory results when compared with that of the daily data (Smakhtin, 2001; Hughes et al., 2003). The algorithm of this method is:

$q_m = \alpha q_{m-1} + \beta(1+\alpha)(Q_m - Q_{m-1})$ (5-1)

$QB_m = Q_m - q_m$ (5-2)

Where:

q is part of the monthly flow which can be attributed to high-flow events or runoff,

Q is total monthly flow (original streamflow time series),

QB is part of the total monthly flow which could be attributed to baseflow,

α is filter parameter,

m is the index of the current month in a time series,

m-1 is the index of the previous month.

Hughes et al. (2003) introduces the parameter β in replace of 0.5 in the above algorithm and sets its range as $0<\beta<0.5$. However in the application of this method, it is found that parameter a is flexible enough or has almost the same efficacy to control the shape and the volume of the separated baseflow. Hence parameter β is fixed to 0.5 in present study and only the parameter a is adjusted to simulate the baseflow separation process.

No one has tried to endue the recursive digital filter method with a hydrological meaning and the opinion is held that it is not based on the real knowledge of the hydrological processes (Hughes et al., 2003). However, by looking at the above Formula (5-1), such explanation might be made that the surface runoff occurred on a specific time step is made up of two components, the surface runoff in the previous time step and the difference between the total flow of the current time step and the previous time step. Apparently surface runoff component of streamflow hydrograph is increasingly dependent on the parameter α; on the other side, baseflow is decreasingly dependent on the parameter α. Consequently, lower α will lead to relatively larger baseflow volume and higher α will produce smaller one.

When assigning the filtering parameter values for α, Smakhtin (2001) recommend that a starting point of 0.925 is applicable for most of the monthly baseflow separations in regions where MAPs range from 600 to 1100 mm in South Africa. He suggested that for semi-arid and arid regions with MAPs less than 600 mm, the filter value can be increased by about 2% and in regions where MAP is over 1100 mm, the filter value can be decreased by 2%. These recommendations may be used for reference but not for arbitrary rote use. Almost all of the TMG outcrop areas are mountainous and has quite thin soil layer, which gives rise to the idea that more surface runoff will occur than in other geological settings with the same rainfall MAPs. In other words, baseflow could be less. This is confirmed by observing the peak time of rainfall and streamflow on the same chart. On each of the existing studied 11 gauging stations, the peak value of rainfall and streamflow occurs in the same month in more than 90% of the observation years. In less than 10% of the years the peak values of streamflow only lag one month behind the peak month of rainfall.

According to the aforementioned statistical analysis, the estimate of the filtering parameter α on a regional scale should be modified when applied to TMG outcrop areas considering the factors of geomorphology and surface soil layer. Another modification is to change the threshold value of MAP of 1100mm to 1000mm because the rainfall differences between regions are not detailedly delineated in the existing rainfall isoline map in WR90. In terms of Smakhtin's recommendations, in this study an increasment of 0.04 is added to the parameter α accounting for the geological and geomorphological characteristics of TMG outcrop areas impacted on baseflow. Finally the values of α are set to range from 0.945 to 0.985 with different MAP values.

With the recursive digital filter low-frequency baseflow can be separated from the stream flow by analyzing the stream flow hydrographs. However if or how much groundwater has contributed to the baseflow is still a question, although baseflow is usually arbitrarily regarded as groundwater discharge in many practical experiences. At this stage, especially for a regional estimation, it is not realistic to differ clearly groundwater discharge from the baseflow; nevertheless baseflow can be regarded as an upper limit estimation of groundwater discharge derived from stream flow. For the estimation of total baseflow related to TMG aquifers, the assumption is made that all the streams located on the TMG outcrop areas has a losing characteristic and only streams flowing across the outcrop areas are taken into account, while on the non-outcrop areas, because of TMG aquifers are mostly deep buried, the stream flow is assumed to have no interaction with TMG aquifers but the overlying layers, i.e. Bokkeveld Group.

The monthly streamflow data for each quaternary catchment in South Africa has been reconstructed from 1920 to 1989 in WR90, providing an ideal basis for this study. The same technique is also used to the data series from streamflow gauging stations intending to validate the result derived from the quaternary catchments baseflow separation for some catchments.

The manipulation of baseflow separation for quaternary catchments includes the following procedures:

- Prepare the quaternary catchment map with the attributes of "MAR" (Mean Annual River flow) for TMG outcrop areas in GIS. This can be done by clipping TMG outcrop areas from the SA quaternary catchment map with the specified boundary. The MAR values are available on primary, secondary, tertiary and quaternary catchment scales and the values for quaternary catchments are used. The ratios of the clipped catchment area to the original catchment area for each quaternary catchment are calculated and added to the attribute table.
- The simulated or reconstructed monthly streamflow history data for each quaternary catchment in TMG outcrop areas are extracted from WR90, which provides the original streamflow data input for the baseflow separation process.
- By simply programming the separation technique described by Equation (5-1) in Excel, monthly baseflow volumes for each quaternary catchment in TMG outcrop areas are successfully simulated. The annual baseflow volume is obtained by adding the monthly volumes for each quaternary catchment.
- The result of the annual baseflow volume in the previous step is for the original area of each quaternary catchment. The actual annual baseflow volume for each clipped area can be calculated by multiplying this value by the ratio of the clipped area to the original area for each quaternary catchment.

The ultimate result of annual baseflow separation is linked to the quaternary catchment map in GIS and the spatial distribution map of baseflow is generated based on the linked attribute fields. Fig. 5-10 and Fig. 5-11 show the spatial distributions of baseflow in TMG outcrop areas in the unit of $10^6 m^3$ and mm respectively. The results of annual baseflow volume for quaternary catchments in TMG outcrop areas are listed in Appendix 2. The total annual baseflow volume in TMG outcrop area is $1082.97 \times 10^6 m^3$ /yr or 34340.89 *l /s*.

Table 5-4 lists the baseflow separation result for each gauge station and the BFI (Baseflow Index) is given as well.

For the convenience of study, only those stations that gauge the whole quaternary catchment(s) are selected to calibrate the baseflow separation results, including E1R002, H2R002, L8R001, K9R001, M1R001. The comparison is showed in Table 5-5.

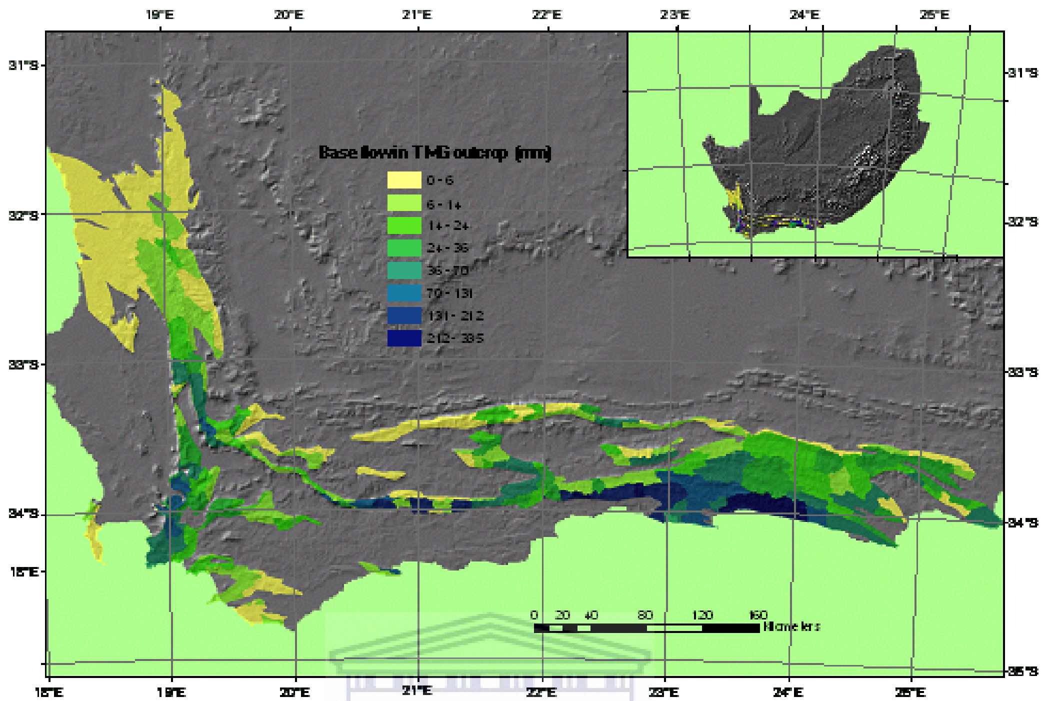


Fig. 5-10 Spatial distribution of Mean Annual Baseflow (mm) in TMG outcrop areas

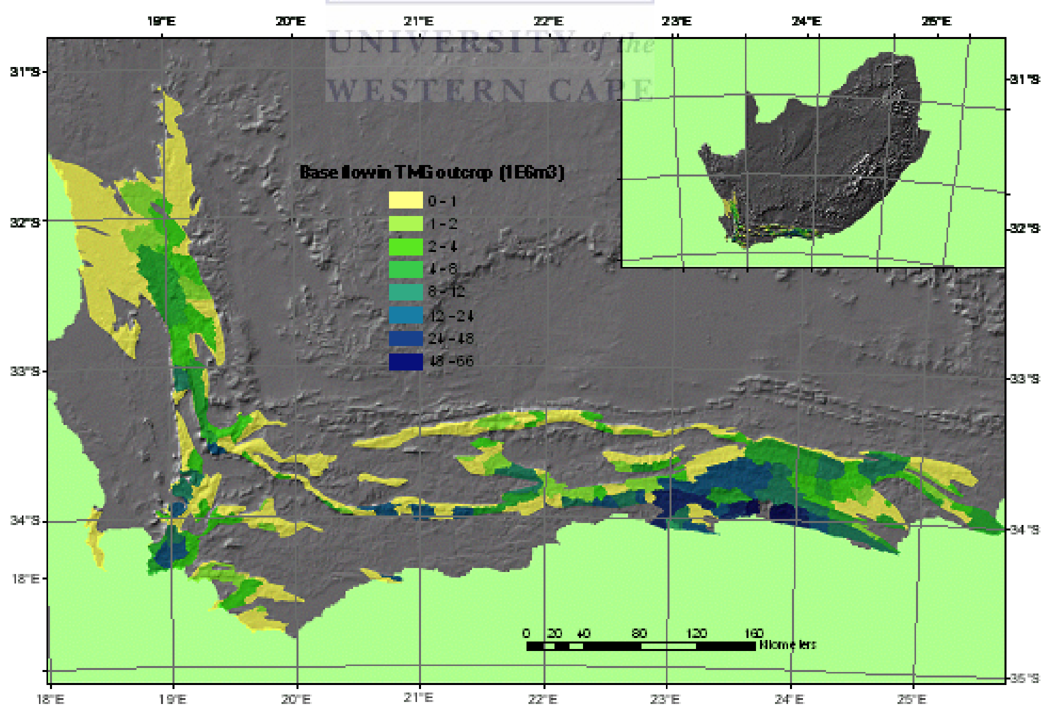


Fig. 5-11 Spatial distribution of Mean Annual Baseflow (Mm^3) in TMG outcrop areas

Table 5-4 Baseflow separation results of the streamflow gauge stations related to TMG

Station No.	MAP (mm)	Parameter *a*	MAR (Mm^3)	MAS (Mm^3)	MAB (Mm^3)	BFI (%)
E1R001	250	0.985	396.1	286.6	109.5	27.6
E1R002	350	0.985	405.5	363.3	42.2092	10.4
H2R001	600	0.965	19.5	16.0	3.5	17.8
H2R002	600	0.965	5.6	4.7	0.9	15.6
G1R002	1000	0.945	71.3	51.0	20.3	28.5
G4R001	900	0.965	43.8	36.2	7.5	17.2
G4R002	900	0.965	54.7	41.6	13.1	23.9
L8R001	400	0.985	187.1	153.6	33.6	17.9
K9R001	700	0.965	53.4	44.0	9.4	17.6
K1R001	400	0.985	2.4	2.3	0.1	4.8
K2R001	700	0.965	3.8	2.7	1.2	30.3
H4R003	400	0.985	2.8	2.7	0.1	4.8
H6R002	1000	0.945	27.0	22.3	4.7	17.5
J1R001	300	0.985	3.5	3.4	0.1	3.9
H9R001	600	0.965	10.1	7.3	2.8	27.9
M1R001	600	0.965	16.0	12.9	3.1	19.3

MAR: Mean Annual Riverflow;

MAS: Mean Annual Surface runoff;

MAB: Mean Annual Baseflow;

BFI: Baseflow Index, the ratio of baseflow to total streamflow.

Table 5-5 Baseflow separation results of stream gauge station and Quaternary catchment

Station No.	Gauged QCat(s)	QCat(s) MAP Range (mm)	QCat(s) MAR (Mm^3)	QCat(s) MAB (Mm^3)	QCat(s) BFI (%)
E1R002	E10A-E10G	400-1000 (350)	404.0 (395.8)	77.0 (42.2)	19.1 (10.4)
H2R002	H20C	500-700 (600)	3.6 (5.5)	0.7 (0.9)	18.7 (15.6)
L8R001	L82H	400-800 (400)	189.0 (187.1)	46.2 (33.6)	24.4 (17.9)
K9R001	K90A-K90B	700-800 (700)	56.0 (53.4)	13.9 (9.4)	24.9 (17.6)
M1R001	M10A	400-600 (600)	16.0 (16.0)	2.7 (3.9)	16.7 (19.3)

* Values in brackets are data derived from corresponding gauge stations.

Theoretically, the Baseflow Indexes (BFIs) derived from the quaternary catchments and from the corresponding gauge stations are supposed to be the same. However, as shown in Table 5-5, the differences do exist. This may partially be attributed to the facticity of original data. A more important reason is that the different MAP values used as reference to decide the value of parameter α in the process of the baseflow separation. Taking gauge station E1R002 as an example, the MAP value 350mm is used in terms of the MAP value of the corresponding rainfall zone, accordingly the lowest α value of 0.985 is used to simulate the baseflow and from which the BFI of 10.4% is obtained. On the other side, the gauged station E1R002 gauges the quaternary catchments from E10A to E10G, which span the region with MAP value ranging from 400 to 1000 mm. A range of α value from 0.945 to 0.985 is sequently used for the baseflow separation of these quaternary catchments based on their MAP values, respectively. Obviously the BFI derived from E10A to E10G is higher than that from the E1R002 station. As an example, the baseflow separation results from the stream gauge station L8R001 and from the quaternary catchment L82H are plotted with the total stream flow in Fig. 5-12 and Fig. 5-13.

From the abovementioned analyses baseflow separation results from both gauge stations and quaternary catchments and their comparison, it can be concluded that the latter is more suitable and reliable for a regional evaluation in that the data from the quaternary catchments have been spatiotemporally averaged and smoothed, consequently more representative. The data from the stations are more specific and suitable for site study.

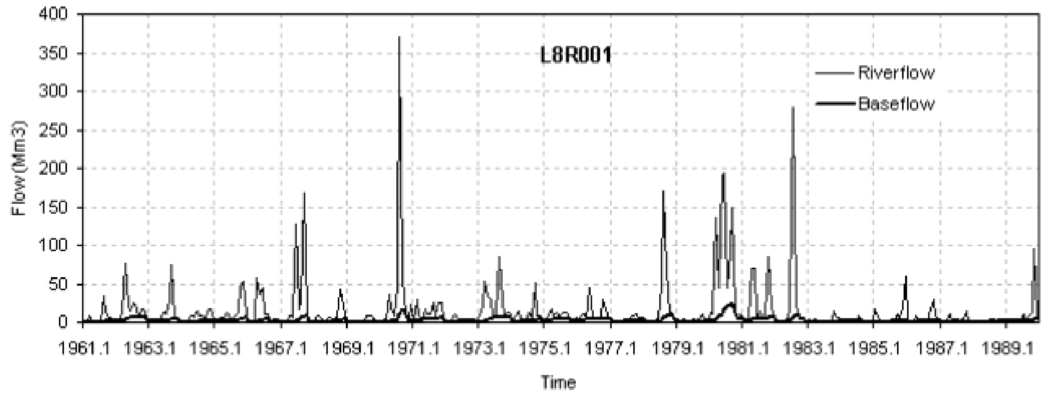


Fig. 5-12 Baseflow separation result for stream gauge station L8R001

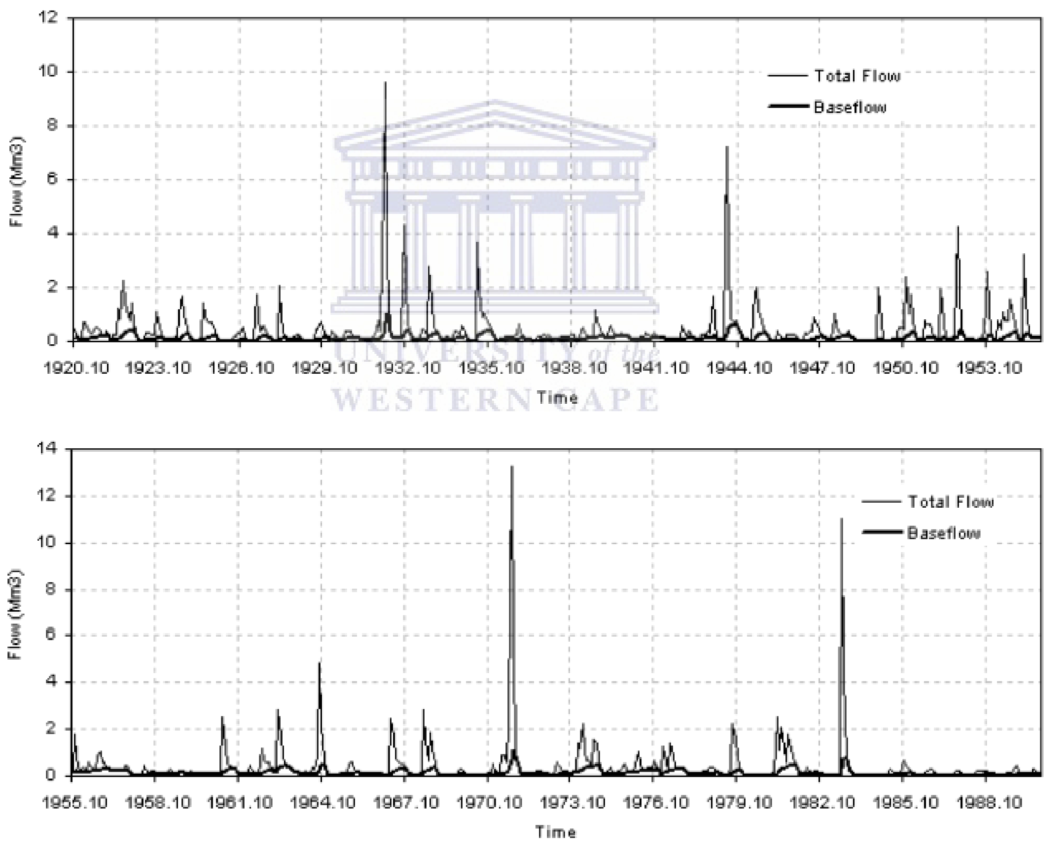


Fig. 5-13 Baseflow separation result for quaternary catchment L82H

5.3.2.3 Baseflow recession

If a long history streamflow data in a catchment are available on a more detailed basis, another analysis, baseflow recession, could be performed to estimate groundwater discharge or recharge of the catchment. It can be observed that from the stream hydrograph in the previous section, during dry weather, water stored in the catchment is depleted by soil-water, groundwater drainage and evapotranspiration. These processes occur at various rates in different time and space, therefore are difficult to quantify. On a typical stream hydrograph (Fig. 5-8), after a critical time following a precipitation event when overland flow and interflow are no longer contributing to streamflow, the hydrograph of a stream will typically decay exponentially. Discharge during the decay period is composed entirely of groundwater contributions as the stream drains water from the groundwater storage, which is baseflow recession. For a specific catchment, the baseflow recession is a function of the overall topography, drainage patterns, soils, and geology of the catchment.

The baseflow recession curve shows the process of natural groundwater storages feeding the stream and it contains valuable information on groundwater storage properties and aquifer characteristics. It can also be a convenient and powerful tool to do hydrological analysis. Tallaksen (1995) contributed a detailed review on recession analysis traced back to studies of Boussinesq in 1877 and Maillet in 1905. He summarized and exemplified the application of recession analysis in many aspects of water resource planning and management, such as low flow forecasting, mathematical modeling, hydrograph analysis, frequency analysis, indexing the storage capacity of the catchment, and so on. The analytical expression, derivation of the characteristic recession, optimization of parameters and time variability in recessions are also reviewed by Tallaksen (1995), which provides a solid base for the future researchers. Though Tallaksen's review has covered a wide area of baseflow recession analysis, its application to the quantification of recharge or dynamic storage of groundwater was not discussed. In this section, the most commonly used baseflow recession expression is presented and applied to one of the quaternary catchments in TMG outcrop area to estimate the recharge quantity.

Theoretically, the slope of baseflow recession is supposed to be consistent for a given catchment and independent of the magnitude of precipitation event or peak flow. However in practice this condition can rarely be met because the recession is also influenced by the variability of evapotranspiration. Here we assume that the hydrograph of a stream at a critical time following a precipitation event (when all groundwater discharge to the stream is contributed by groundwater) will decay following an exponential law. This baseflow recession is described by:

$$Q = Q_0 e^{-kt} \tag{5-3}$$

Where Q is the flow at some time t after recession has started, Q_0 is the flow at the start of baseflow recession, k is the recession constant for the basin, and t is time.

At the beginning of recession t=0 and Q=Q_0, the recession constant k can be expressed as:

$$k = -\left(\frac{1}{t}\right)\ln\left(\frac{Q}{Q_0}\right) \tag{5-4}$$

Obviously k is a number larger than 0 and less than 1. It will be the large for flat recessions (close to 1), and the small (close to 0) for steep recessions. Usually karstified terrains have flat recessions because much of the drainage occurs in the subsurface, on the other side, glacial sediment and granitic terrains have steep recessions.

Baseflow recession curve can be used as an effective tool to estimate groundwater recharge, discharge and dynamic storage (Wittenberg, 1999; Peters, 1994). The following procedures are involved:

1) A logarithmic, multi-year baseflow recession curve is available for the analysis. The slope of the recession curve (which should be a straight line) is the recession constant. Then the recession expression becomes:

$$Q = \frac{Q_0}{10^{t/t_1}} \tag{5-5}$$

Where Q_0 is the discharge at time t=0, $t_1$is the time 1 log cycle later (or the time that takes the baseflow to go from Q_0 to 0.1 Q_0), and t can be any time during the recession. In the case of t=t_1, Equation (5-5) becomes:

$$Q = \frac{Q_0}{10} \tag{5-6}$$

2) The total volume of baseflow discharge regarding a recession can be calculated by integrating (5-6) over the times of interest

$$V = \int_{t_0}^{t} Q dt = -\left.\frac{Q_0 t_1 / 2.3}{10^{t/t_1}}\right|_{t_0}^{t} \tag{5-7}$$

Where t_0 is the starting time of interest, the other denotations are the same as above.

3) To calculate total potential baseflow discharge for a complete groundwater recession (for the first year of the selected continuous multi-years, or year 1), let t_0 equals zero and t equals infinity, Equation (5-7) can be simplified to

$$V_{tp1} = \frac{Q_0 t_1}{2.3} \tag{5-8}$$

Where V_{tp1} is the total potential groundwater discharge. This volume is defined as the total volume of groundwater that would be discharged during an entire baseflow recession if the depletion could proceed continuously. This is an ideal condition and in physical circumstance the recession is usually interrupted by the next precipitation event before the entire potential groundwater discharge is depleted. This volume can also be regarded as the total volume of water in storage at the beginning of the recession.

4) Calculate the discharge that actually takes place during a baseflow recession.

$$V_t = \frac{V_{tp}}{10^{t/t_1}} \qquad (5\text{-}9)$$

In this equation the time t represents the duration of the actual entire recession from the start to the end, and it is easy to understand that potential discharge is greater than actual discharge.

5) Calculate the remaining potential groundwater discharge at the end of the recession for the first year.

$$V_r = V_{tp1} - V_t \qquad (5\text{-}10)$$

6) Calculate the potential discharge V_{tp2} for the second year (year 2), and then subtract the actual discharge (year 1) from the potential discharge of year 2. The difference describes the groundwater recharge to the basin between the two recessions.

$$R = V_{tp2} - V_t \qquad (5\text{-}11)$$

7) The above steps can be done continuously for the selected multiple years to calculate the recharge for each year.

The aforementioned method has been automated in Excel. Initially we intended to apply it to the whole history records of streamflow (monthly baseflow data from 1920 to 1989 derived from the previous section) for all of the quaternary catchments in TMG outcrop to simulate the recharge continuously for the 70 years, and it could be a calibration to the soil water balance approach introduced in Chapter 4. Unfortunately a considerable time variation in the baseflow recession has been found from most of the catchment. According to Tallaksen's review (Tallaksen, 1995), the variation is not only dependent on physical factors like climate influence, but also on the recession model and calculation procedures selected. In other word, variability may occur by using a fixed recession equation to simulate a wide range of flow records. To minimize the uncertainty of the model, more effort is needed to use proper recession equations for different periods of flow records based on their characteristics. This undoubtedly imposes difficulties to the automation task.

Climate influence on the recession includes recharge from precipitation or snowmelt during the recession, losses from evapotranspiration, which are assumed zero during the recession process. One possible solution to the problem of the evapotranspiration loss has been studied before (Farvolden, 1963; Tschinkel, 1963; Reigner, 1966 and Weisman, 1977). A potential recession curve is currently constructed to represent the situation without evapotranspiration losses during the recession. The difference between the potential and actual recession curves is related to the evapotranspiration losses. Unfortunately the construction of such curve is yet not easy.

Besides current climate influence, the previous weather conditions before the start of recession and aquifer types are also the influential factors which arouse the time variation of the baseflow recession. Spatial variability of storm response in larger catchments may lead to the distribution pattern of flow paths in the catchment, which in turn influences the drainage pattern (Laurenson, 1961). Also the occurrence of different types of aquifers or the anisotropy of the specific aquifer adds more to the variability.

Considering these factors, several periods in the quaternary catchment G40A (Fig. 5-14) are carefully selected to implement the baseflow recession analysis because the time variation of the recession during these periods is relatively smaller. The monthly baseflow series of several hydro-years, including 1928 to 1930, 1963 to 1966 and 1985 to 1987, are chosen to estimate the groundwater recharge in the corresponding periods.

Fig. 5-14 The location of quaternary catchment G40A

The quaternary catchment G40A is located near the southeast of Cape flat, covering 71.5 km^2 of surface area. Its northwest boundary is the Hottentots Hollandberg Mountain. The whole catchment is controlled by a syncline striking E20°N, in which the exposed bedrock, from the core to the border, is Bokkeveld, Nardouw Subgroup, and Peninsula Formation. Overall landscape has the feature of higher in northeast and lower in southwest, from 720 meters above sea level to 0m (sea level). A high annual rainfall (over 1000mm) in this area makes the water resource significant. The Steenbras River develops along with the axis of the syncline, from the uppermost point of the catchment, with plenty of water coming from the mountainous area.

The baseflow recession calculation for catchment G40A is done as follows.

(1) 1928 to 1931

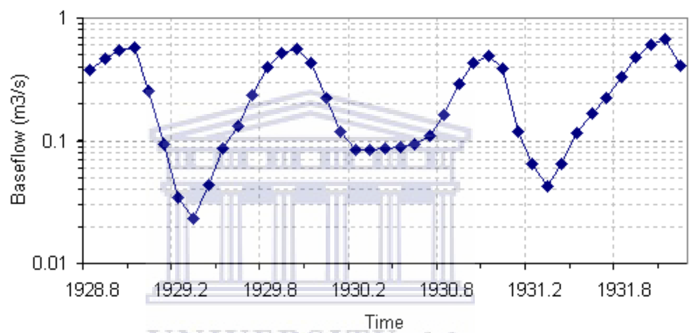


Fig. 5-15 Baseflow recession of G40A (1928 – 1931)

In November of 1928, the baseflow discharge reached the highest value and from this month, the baseflow recession started. The average discharge of this month is 0.569 m^3/s (Q_0), which is averaged from the monthly value. According to the recession chart and calculation, it takes about 2.616 months to decrease to the amount of $Q_0/10$. Therefore the potential baseflow discharge at the start of the recession is:

$$V_{tp(1928.11)} = \frac{Q_0 \cdot t_1}{2.3} = \frac{0.569 \times 2.616 \times 30d \times 24h \times 3600s}{2.3} = 1.68 \times 10^6 m^3$$

After 4 months, in March of 1929, the baseflow discharge reached the minimum value of 0.023 m^3/s, the baseflow recession stopped and the recharge started. The actual baseflow discharge during this recession period can be calculated:

$$V_{t\ (1928.11\text{-}1929.3)} = \frac{V_{tp(1928.11)}}{10^{t/t_1}} = \frac{1.6784 \times 10^6}{10^{4/2.616}} = 0.05 \times 10^6 m^3$$

Then the remaining potential baseflow discharge can be calculated:

$$V_{r(1928)} = V_{tp(1928.11)} - V_{t(1928.11-1929.3)} = 1.6784 \times 10^6 - 0.0497 \times 10^6 = 1.63 \times 10^6 m^3$$

The next baseflow recession started from October of 1929, with a potential discharge ($V_{tp(1929.10)}$) of $1.6693 \times 10^6 m^3$. Then the recharge from March of 1929 to October of 1929 is easy to derive:

$$R_{(1929.3-1929.10)} = V_{tp(1929.10)} - V_{r(1928)} = 1.6784 \times 10^6 - 1.6287 \times 10^6 = 0.04 \times 10^6 m^3$$

The calculation is continued to derive the recharge for the successive years in this period. The results are:

$$R_{(1930.2-1930.11)} = V_{tp(1930.11)} - V_{r(1929)} = 2.0477 \times 10^6 - 1.6199 \times 10^6 = 0.43 \times 10^6 m^3$$

$$R_{(1931.3-1931.11)} = V_{tp(1931.11)} - V_{r(1930)} = 2.8639 \times 10^6 - 1.8747 \times 10^6 = 0.99 \times 10^6 m^3$$

(2) 1963 to 1966

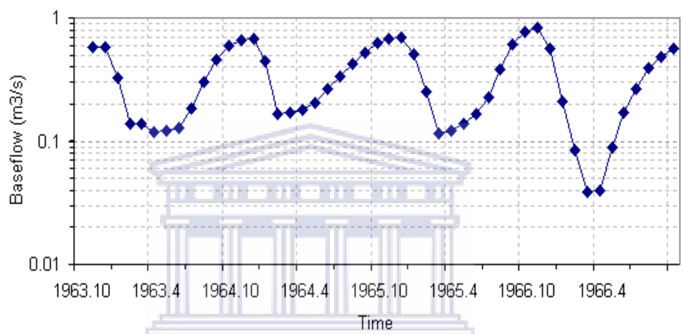


Fig. 5-16 Baseflow recession of G40A (1963 – 1966)

$$R_{(1964.3-1964.11)} = V_{tp(1964.11)} - V_{r(1963)} = 2.2898 \times 10^6 - 1.8804 \times 10^6 = 0.41 \times 10^6 m^3$$

$$R_{(1965.1-1965.11)} = V_{tp(1965.1)} - V_{r(1964)} = 2.3418 \times 10^6 - 1.8012 \times 10^6 = 0.54 \times 10^6 m^3$$

$$R_{(1966.2-1966.10)} = V_{tp(1966.10)} - V_{r(1965)} = 2.8502 \times 10^6 - 2.1110 \times 10^6 = 0.74 \times 10^6 m^3$$

(3) 1985 to 1987

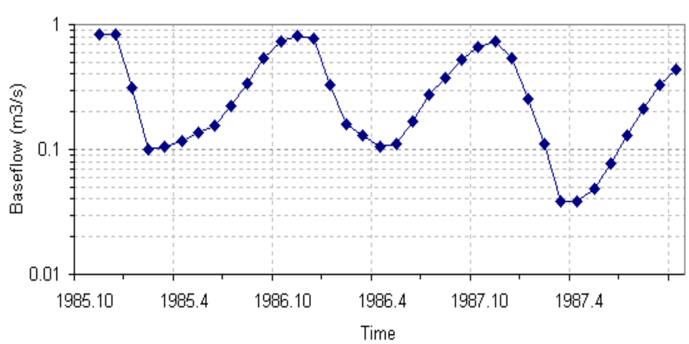


Fig. 5-17 baseflow recession of G40A (1985 – 1987)

$$R_{(1985.2-1985.10)} = V_{tp(1985.10)} - V_{r(1984)} = 2.6589\times10^{6} - 1.9248\times10^{6} = 0.73\times10^{6}\,m^{3}$$

$$R_{(1986.1-1986.10)} = V_{tp(1986.10)} - V_{r(1985)} = 2.5786\times10^{6} - 2.4324\times10^{6} = 0.15\times10^{6}\,m^{3}$$

$$R_{(1987.3-1987.10)} = V_{tp(1987.10)} - V_{r(1986)} = 2.9211\times10^{6} - 2.5360\times10^{6} = 0.39\times10^{6}\,m^{3}$$

The results of the above calculations indicate that the recharge derived from the baseflow recession varies a lot from year to year. This in other side reflects that the groundwater recharge, in the form of difference between potential and actual groundwater discharge, is definitely influenced by climate changes, both long periodically and seasonally. Based on the recession analysis, take 0.5 Mm^3 as an approximately averaged value of groundwater recharge, the annual recharge is calculated to be 7mm/year for the catchment, which account for 0.7% of the MAP.

Though baseflow recession is also widely used in quantification of groundwater resource, in our study, it could not be extrapolated to other TMG-related catchments to estimate the groundwater recharge to or discharge from TMG aquifers. The baseflow recession of a catchment is dominated by the process of infiltration, runoff, soil moisture and other hydrological processes, all of which have a close relationship with the size, shape, soils, sediment, bedrock, vegetation and topography of the catchment. Even in catchment G40A, the derived groundwater recharge and discharge is difficult to be decided to have a relationship with TMG aquifers since the stream has hydraulic contact with other aquifers as well. Also, in most cases, surface water catchments don’t coincide with the groundwater catchments, while usually in practice such assumptions are usually made for the convenience of study.

5.4 Summary

The interaction between groundwater and stream is the most common GW–SW interaction type in TMG aquifers. In the mean time baseflow is identified to be a dominated component of groundwater discharge from TMG aquifers.

Using the spatial selection function of GIS, 17 stream gauge stations and 83 rainfall zones are identified in TMG outcrop areas. The long-term climate changes mainly concerning rainfall in TMG outcrop area are studied through the rainfall historic records in TMG outcrop areas, which help to understand the periodicity of streamflow in that the streamflow hydrograph usually has the similar oscillation to that of the rainfall.

A variety of baseflow separation methods are reviewed, from which the digital recursive filtering technique is applied to separate the baseflow from the total streamflow for both the gauge station and quaternary catchment flow records, and then some of the result are compared. It is estimated that the mean annual baseflow amounts to 1.1×10^9 m^3 /yr, which could be regarded as the upper limit of the groundwater discharge from TMG aquifers through streamflow.

The baseflow recession analysis is also carried out on a quaternary catchment G40A at the end of this chapter. The groundwater recharge and discharge could be estimated by this way. Unfortunately because of the relatively high data requirements, this analysis could not be extended to the whole TMG area.

6. The aquifer response to pumping in Kammanassie Mountains

6.1 Introduction

Since TMG groundwater has been identified as the “hidden treasure”, a number of ongoing research studies covering the broad type areas have been conducted, which usually coincide with existing wellfields where quantitative information can be correlated and analyzed. Some of these type areas are introduced in section 1.2.2.5. Groundwater flow models may also be constructed with the exiting data. In this chapter, Kammanassie Mountains is selected as a case area to study the response of TMG aquifers to long-term pumping scheme. Both the past pumping scheme and the future pumping scheme are modeled by different scenarios.

Kammanassie Mountains is located in the eastern section of the Klein Karoo area (Kotze, 2002) and has been part of the KKRWSS (Klein Karoo Rural Water Supply Scheme). The abstraction has been effected for about fifteen years. As shown in Fig. 6-1, Klein Karoo area comprises a broad valley surrounded by Outeniqua, Swartberg, Kammanassie, and Rooiberg Mountains. The Toorwater hotspring issued from Cango fault zone is situated on the northeast of Kammanassie Mountains, and Calitzdorp hotspring occurs at the foothill of Rooiberg Mountains in the middle-west part of the area, which may indicate the regional groundwater flow regime.

As part of the Eastern Sector of the KKRWSS, Kammanassie Mountains area is about 630km^2, comprising three blocks of TMG window areas or Peninsula outcrops which are actually in the core area of Kammanassie mega-anticline, surrounded by Nardouw Subgroup and Cedarberg Shale (Fig. 6-2). The whole study area can be identified as an intermediate groundwater flow regime where the contact between Nardouw and neighboring Bokkeveld Group acts as flow boundary. Three local flow regimes can be identified in the window areas mainly within the boundaries of Cedarberg Shale aquitard. Groundwater has been extracted from both the Peninsula and Nardouw Aquifer. 13 main production boreholes were drilled in the study area, 4 of which in Peninsula Aquifer and 9 in Nardouw Aquifer. The associated abstraction and water level data are available. Some other production boreholes in this area are privately owned and mostly situated in Nardouw outcrop. Monitoring boreholes and data are also available. From borehole location map (Fig. 6-3), it can be observed that most of the boreholes were drilled in fault zones or the contacts between Nardouw Subgroup and Bokkeveld Group, intending to intercept more potential of groundwater.

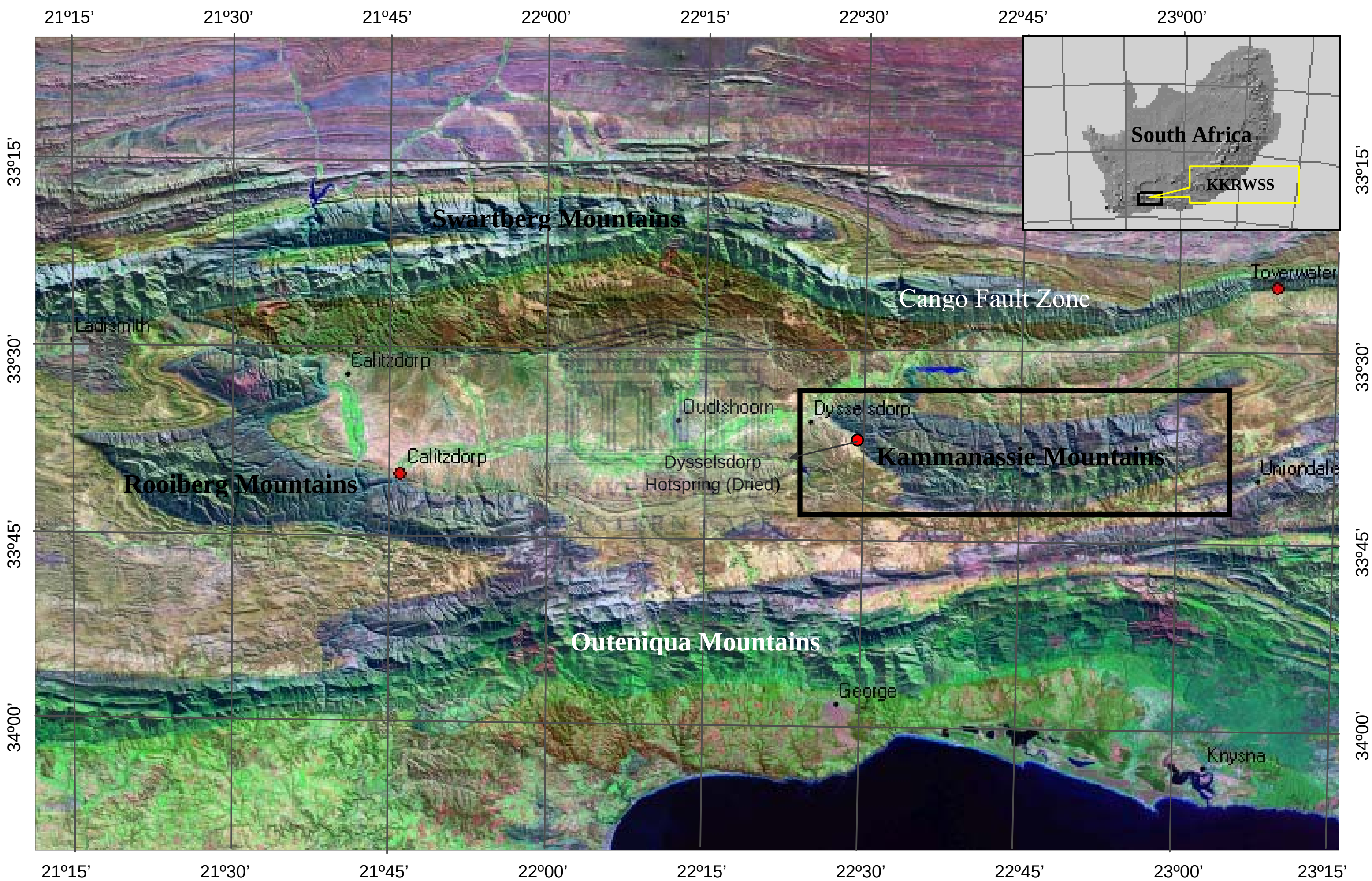


Fig. 6-1 Locality map of KKRWSS and Kammanassie Mountains

With the utilization of various associated software and based on preliminary water balance calculation, Kotze (2002) estimated recharge rate and proposed management plan of the groundwater abstraction in study area.

In this chapter, the previous studies are evaluated and provide the basis for this study. A 3D model of the Kammanassie area is generated, aiming to improve the understanding of the conceptual hydrogeological model. The numerical groundwater flow modeling is established for the Vermaaks Window area (Peninsula outcrop in the western plunge nose of Kammanassie anticline, see Fig. 6-2 and 6-3) to simulate the effects of groundwater abstraction on the Peninsula Aquifer and the inverse model is carried out as well to calibrate the relative recharge rates and aquifer properties.

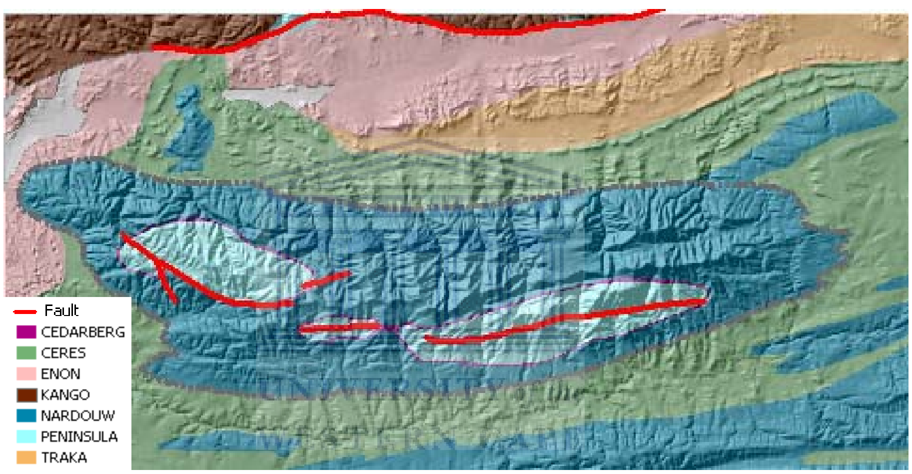


Fig 6-2. Simplified Geology map of Kammanassie Mountains

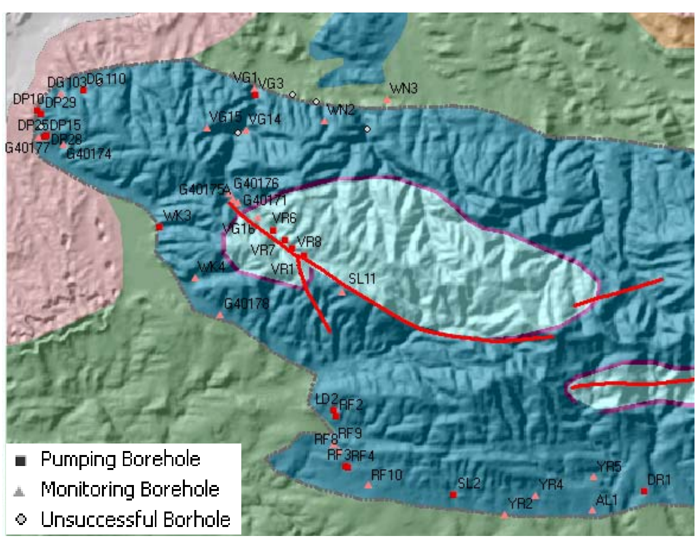


Fig. 6-3 Borehole location map of Kammanassie Mountains

6.2 Data analysis

6.2.1 Precipitation

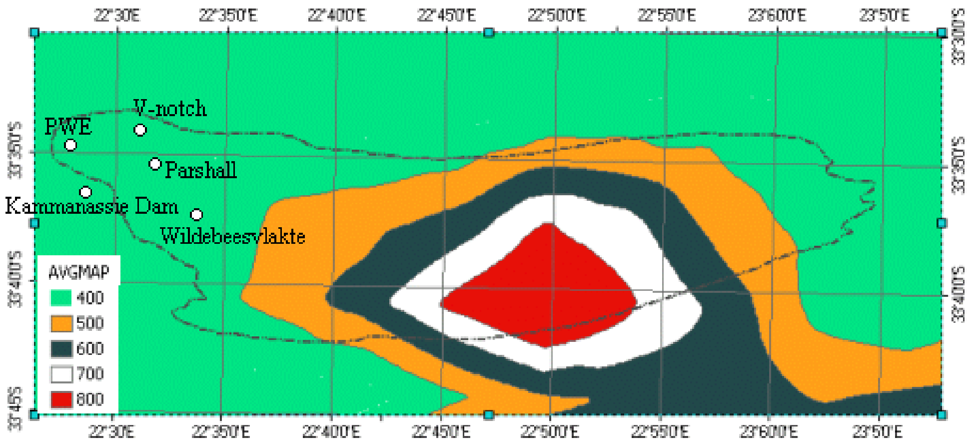


Fig. 6-4 Mean Annual Precipitation (MAP) in Kammanassie Mountains

The spatial and temporal rainfall variability and trends in Kammanassie area has been detailedly studied by Wu (2005). The long-term average annual precipitation for the study area ranges from 400mm to 800mm (Fig. 6-4). Five rainfall stations as shown in Fig. 6-4 are selected to do the long-term and short-term rainfall analysis, namely Kammanassie Dam, Purification Work East, V-notch, Parshall and Wildebeesvlakte. The monthly average rainfall over 76 year (1921-1996) is summarized in Fig. 6-5. It can be observed that there is no distinctive bimodal seasonal cycle in this area, however, relatively higher rainfall occurs in March, April and November, which may indicate higher recharge potential in these months.

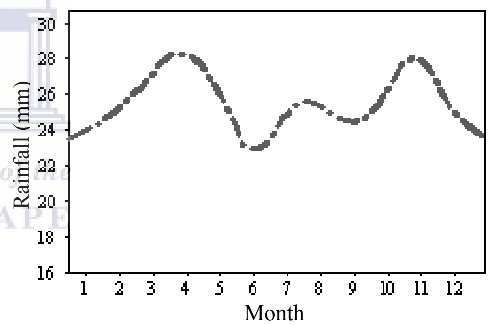


Fig. 6-5 Monthly average rainfall from 1925 to 1996 (after Cleaver et al., 2003)

According to Wu (2005), a slightly positive trend occurred in the Kammanassie Dam rainfall station since 1925, however, this trend does not necessarily indicate that the study area has experienced the increasing rainfall. Except Kammanassie Dam rainfall station, the other four stations are all located in mountainous area and used to perform the CRD (Cumulative Rainfall Departure) analysis. From Fig. 6-6, it can be observed that the four stations have similar rainfall patterns but different maltitudes. The same condition is found in the CRD patterns of the four stations (Fig. 6-7).

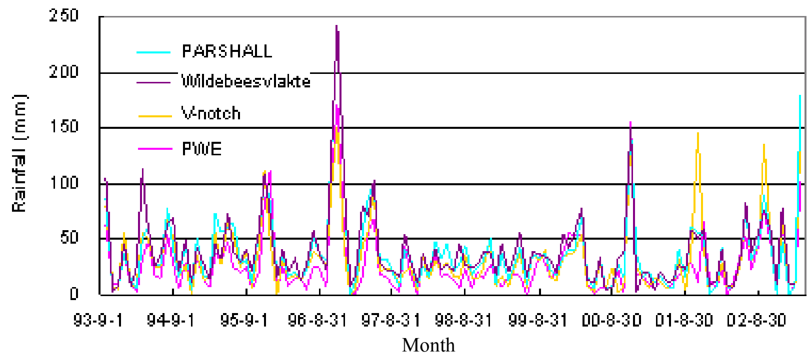


Fig. 6-6 Rainfall patterns in the Kammanassie Mountains

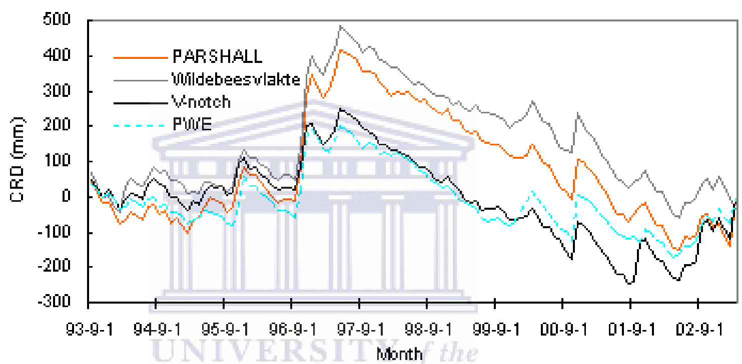


Fig. 6-7 CRD patterns in the Kammanassie Mountains

6.2.2 Evapotranspiration

Average annual potential evaporation is about 1700-1800mm in Kammanassie Mountains and it is almost 50% less during April to September. Higher evapotranpiration occurs in the summer, from October to March, which can also be reflected by the decline of groudnwater level and low spring flow rate during the time.

6.2.3 Surface flow

Kammanassie Mountains is drained by the upper reaches of two rivers Olifants River and Kammanassie River. Seven quaternary catchments are involved as showed in Fig. 6-8. A small but important river, Vermmaks river was not included in the WR90 river database. It is marked in Fig. 6-8 according to the DEM.

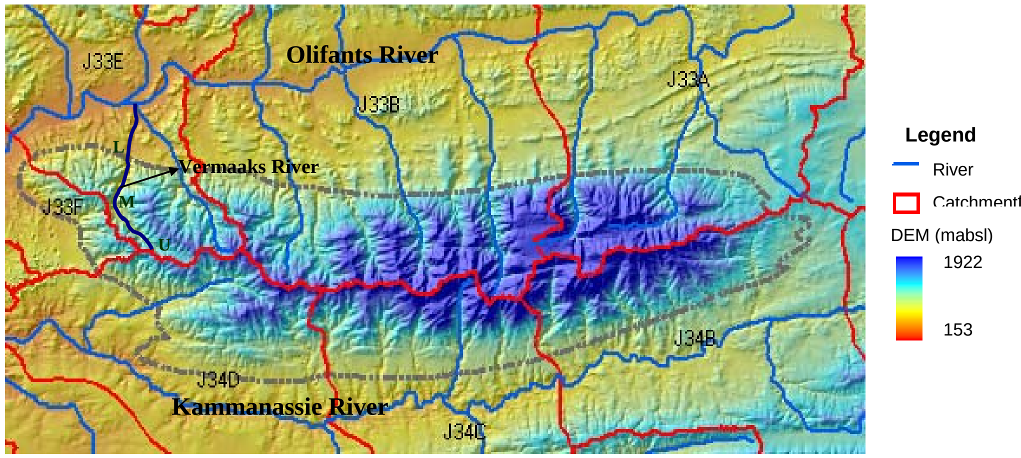


Fig. 6-8 Rivers and Quaternary catchments in Kammanassie Mountains
(L: Lower reach; M: Middle Reach; U: Upper reach of Vermaaks River)

The seven quaternary catchments are all located in the secondary catchment J3. All of them are part of the following quaternary catchments: J33A, J33B, J33E, J33F, J34B, J34C and J34D. The groundwater boundary cannot be simply assumed to coincide with the surface water boundary as the geological boundary usually prevails in groundwater flow regime, such as the Cedarberg aquitard and the contact between Nardouw Subgroup and Bokkeveld Group. According to the distribution of the rivers in this area (all rivers are located in the TMG outcrop area), it could be considered that there is an active interaction between groundwater and surface water. The baseflow separation results in Chapter 5 for this area are listed in Table 6-1. The results show that the average mean annual baseflow is about 21.79% of the mean annual riverflow and is 1.60% of the mean annual precipitation. This is lower than Kotze's estimation, in which 30%-90% of the flow was taken as baseflow of TMG aquifer in Vermaaks river. However, the baseflow separation is based on a quaternary-catchment averaged basis, which cannot be thought that all the rivers have the same response. In fact since 1993 when the pumping started, the ground water level in upper reaches of Vermaaks river area has declined more than 30 meters, which is far lower than the elevation of the riverbed. In such cases, hydraulic relationship can only occur between the river and the water stored in the shallow weathered zone.

Western Kammanassie area includes Vermaaks River catchment (31.6km^2) and Marnewicks catchment (26.4km^2) shown in Fig. 6-9, both of which are delineated from the DEM. The upper reaches of the two rivers are ephemeral, which become more sustained flow in the lower reaches, and drain northward into the Olifants River.

Table 6-1 Baseflow separation results for the catchments in Kammanassie Mountains

Quaternary Catchment	MAR4Q ($10^6 m^3$)	MAP4Q (mm)	Area4Q (Km^2)	Outcrop Area (Km^2)	Area_Ratio (%)	MAB4Q ($10^6 m^3$)	MABOC ($10^6 m^3$)	MAB (mm)	MAB/MAR (%)	MAB/MAP (%)
J33A	5.12	392.53	449.46	173.77	38.66	1.22	0.47	2.71	23.83%	0.69
J33B	9.22	436.91	590.72	220.15	37.27	2.14	0.8	3.63	23.21%	0.83
J33E	24.59	445.73	328.67	115.94	35.27	4.75	1.68	14.45	19.32%	3.24
J33F	11.7	343.28	365.62	47.69	13.05	2.54	0.33	6.94	21.71%	2.02
J34B	12.88	569.32	341.55	211.37	61.89	2.72	1.68	7.95	21.12%	1.40
J34C	21.3	673.55	318.9	243.29	76.29	4.21	3.21	13.2	19.77%	1.96
J34D	7.72	470.83	354.2	179.09	50.57	1.82	0.92	5.13	23.58%	1.09
Average	13.22	476.02	392.73	170.19	44.71	2.77	1.30	7.72	21.79%	1.60
Note: the stream flow data are based on a regional study and extracted from those before 1989.										

6.2.4 Springs and hotsprings

There used to be many cold springs along the lower western slopes of the Kammanassie Range but have dried up since the early 1970's. Some of them occasionally run after rainfall events, according to Mr Haasbroek of Overberg water (Wu, 2005). Three small separate hotsprings emanated in the valley floor below the Bokkraal Wellfield until the early 1970's (Smart, 2000).

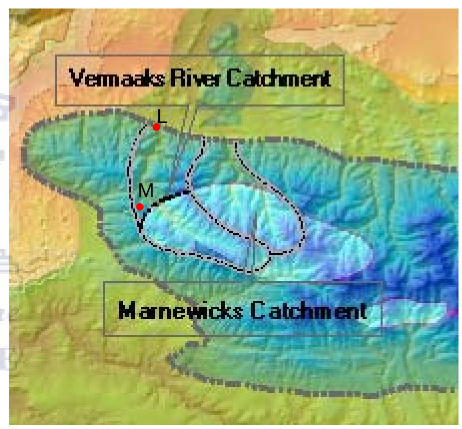


Fig. 6-9 Sub Catchments in western Kammanassie Mountains

Two springs develops along the flow path of Vermaaks River and their locations are marked on Fig. 6-9 as ‘L’ (lower reach) and ‘M’ (middle reach). Fig. 6-10 is a cross section cut through the Vermaaks River. The relationship between the river and the aquifer setting and the relationship between the river and the adjacent boreholes are identified in the figure. Spring 051 (‘M’) is located on the middle reach of the river and used to issue from the shallow deposits. Now it has stopped flowing due to the abstraction of the adjacent pumping boreholes. A V-notch weir for spring monitoring was built on the lower reach of Vermaaks River where the spring (‘L’) is perennial. The monthly spring fluxes have been recorded on this monitoring station. The records from the start of 1994 to the end of 2001 show that the spring flow is more correlated to rainfall (positively, see Fig. 6-11) than to groundwater abstraction from the Vermaaks River Wellfield (negatively, see Fig. 6-12), with the weak correlation coefficients of 0.576 and –0.384 respectively.

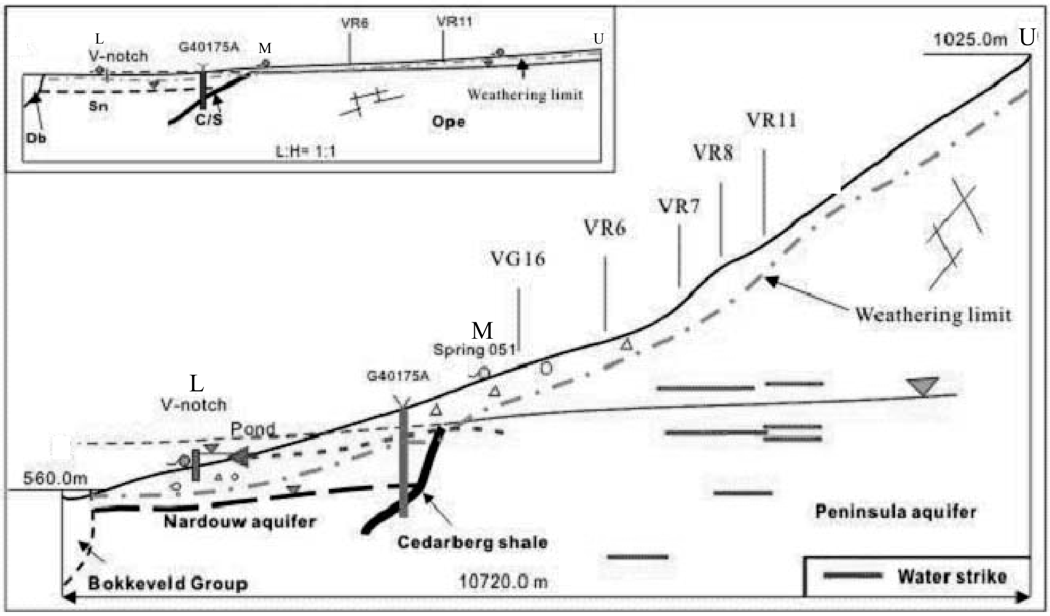


Fig. 6-10 Cross section along with Vermaaks River (after Wu, 2005)

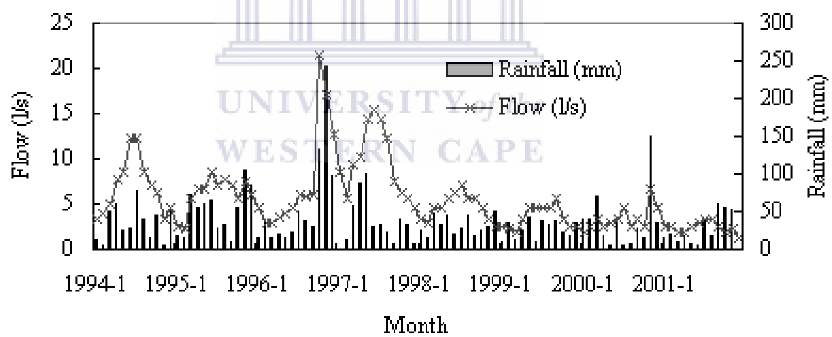


Fig. 6-11 Correlation between spring flow of Vermaaks River and rainfall

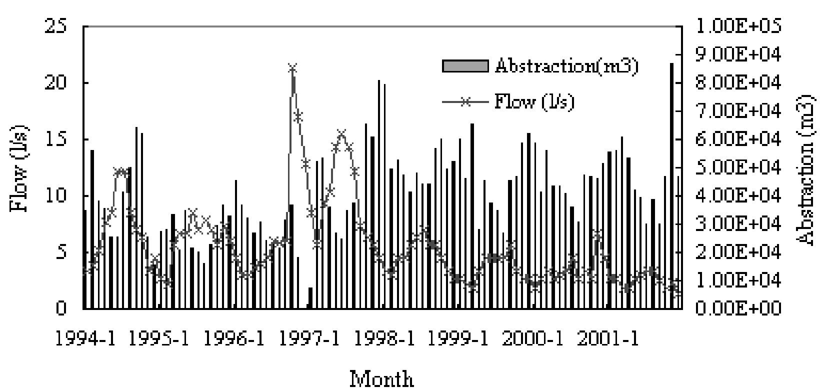


Fig. 6-12 Correlation between spring flow and groundwater abstraction

Three hotsprings occurs in KKRWSS study area, Calitzdorp hotspring, Dysselsdorp hotspring, Toorwater hotspring, as labeled in Fig. 6-1. The Calitzdorp hotspring is situated on a NE-striking fault where the Nardouw Subgroup sandstone faulted against Bokkeveld Group shale (Meyer, 2002). The Dysselsdorp hotspring is also located at the contact between faults in the TMG and Bokkeveld Group but has dried due to the abstraction in Vermaaks River field. Toorwater Hotspring developed on the E-striking Cango fault, where Peninsula Formation sandstone faulted against Enon Formation (Uitenhage Group) conglomerate. Wu (2005) illustrated the relation between interflow, local flow and regional flow by Fig. 6-13, based on the geological setting, locations of hotsprings and water level information in this area. He drew the conclusions as following: the interflow occurs in the mountainous areas with elevation of 220 to 1950m; the local flow may occur 220-1700m and regional flow can flow at depth related to the distribution of the TMG aquifer; and the regional discharge area is located at Calitzdorp hotspring.

6.2.5 Local geology and aquifer setting

Remote sensing interpretation carried out by the CGS has indicated that two major fracture systems prevail in Klein Karoo area, namely E-W striking fault system, which consists long and continuous faults, and N-S striking fault system, in which shorter and more discontinuous fractures predominate (Chevallier, 1999). The two main fracture orientations are NNW and NNE trending and form a conjugate set, which provides extensive opportunity for groundwater storage and flow in this area.

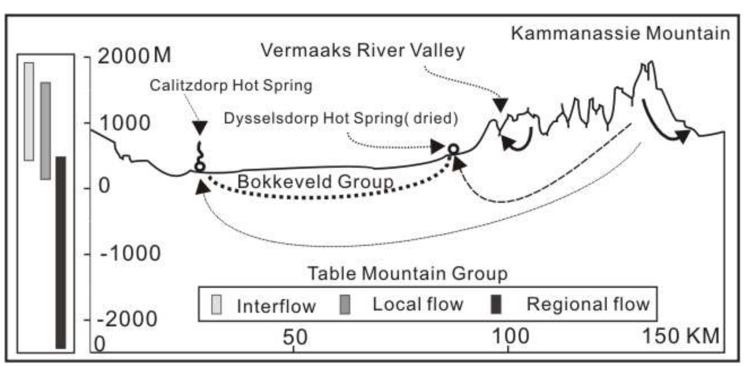


Fig. 6-13 Interflow, local flow and regional flow (after Wu, 2005)

The detailed field geological mapping of the western Kammanassie Mountains was carried out by Hälbich and Greef (1995), including the typical fault, fold, and contact relationships around the periphery of the westward plunging nose of the Kammanassie mega-structure. The mapping is shown in Fig. 6-14. Four downscaling morphological types of faulting are distinguished as follows:

•The 200m wide and 9km long Vermaaks River Fault fracture zone along with the Vermaaks River Valley.

•Smaller faults, e.g. the ESE trending Brilkloof, SSE-trending Leeublad and Rooikrans and three E-W-trending Klapperskloof Faults with sharply defined planes with up to 20m wide breccia zones.

•Breccia, consisting of rounded and rotated fragments in a fine-grained ground mass.

•Homogeneous mass of a very fine-grained cataclasite which is partly recemented and extremely hard.

"Vermaaks Keystone Block" was defined in this area due to the high permeability associated with the extensive faulting. The lineament density map (Fig. 6-15) created from the interpretation of satellite image shows that high density of structures concentrates in the block. Its significance has also been verified by the high yielding production boreholes drilled in this zone.

The Kammanassie Mountains are an eroded remnant of resistant TMG sandstones, also referred to as the Kammanassie mega-anticline. For the Kammanassie Mountains, NW and NE trending open joints are most prominent in the Nardouw Subgroup. In the Peninsula Formation, E-W trending joints are close and filled with quartz, whereas N to NE and NW trending joints are open.

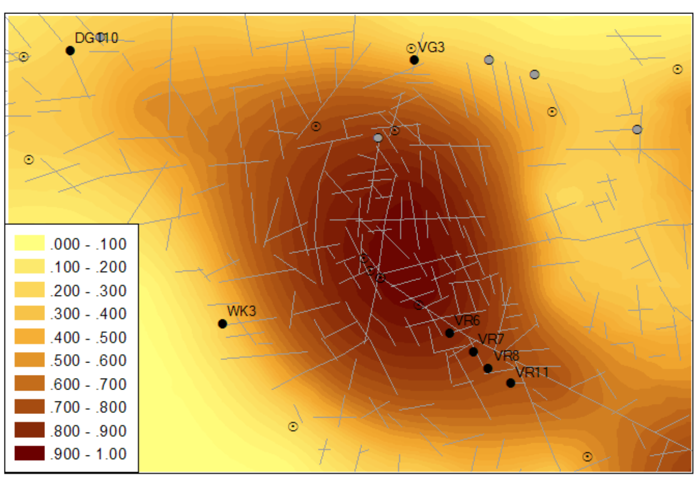


Fig. 6-15 Lineament density map in Vermaaks Keystone Block

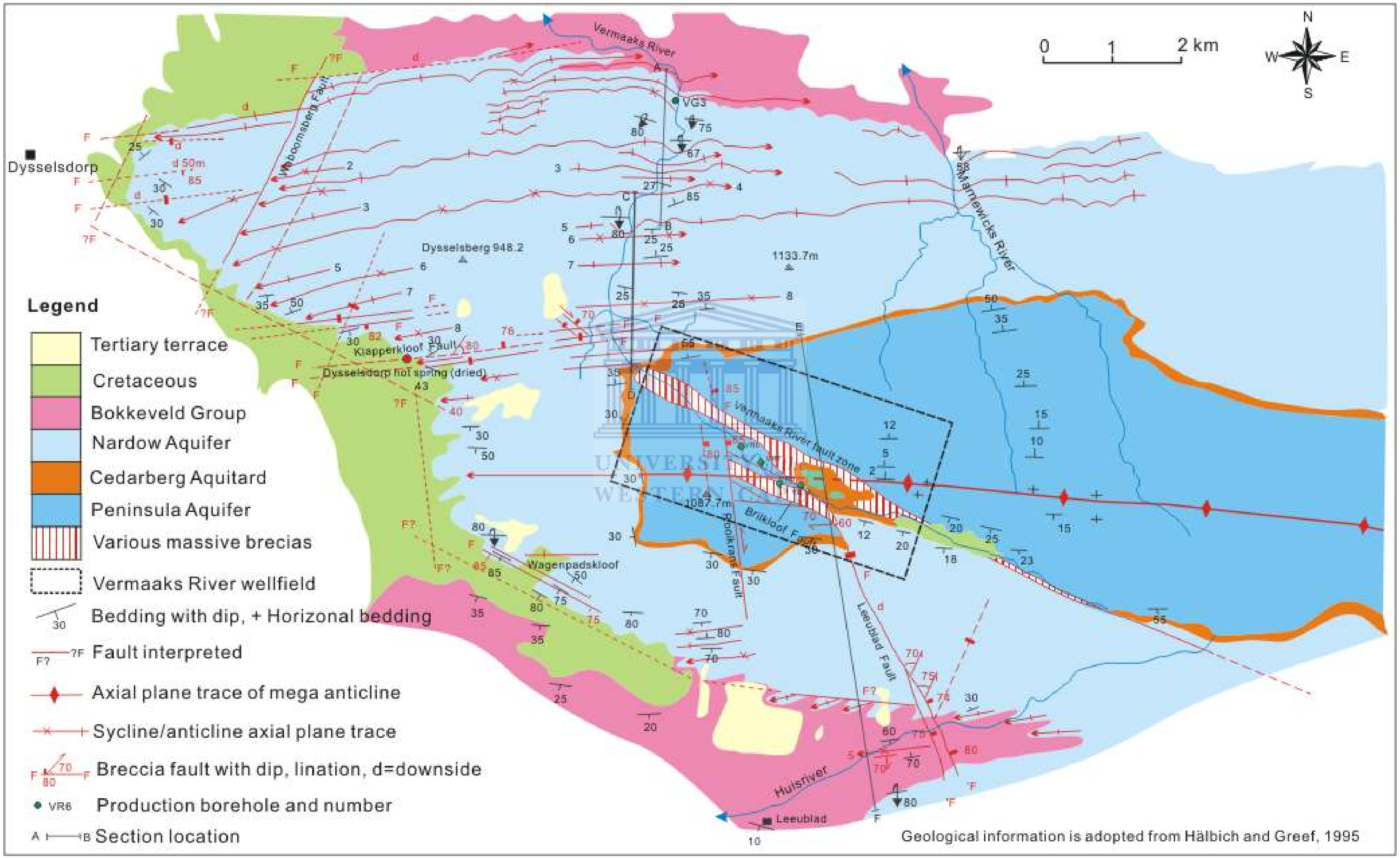


Fig. 6-14 Detailed geological map in the Kammanassie area (after Hälbich and Greef, 1995)

The TMG in this area includes Peninsula and Nardouw Aquifers, which are separated by Cedarberg Aquitard (Fig. 6-2). The aquifers strike EW, coinciding with the axial plane of the Kammanassie mega-anticline. The TMG outcrops form the main recharge area of the aquifers. Alluvial and slope deposits, consisting of sand, gravel and other unconsolidated materials, are distributed at the foot of the mountain and along the valley floor. The thickness of these deposits is up to 15m (Kotze, 2002). The TMG aquifer is likely to receive infiltration from both open fracture networks of the outcrop rocks and the loose deposits.

6.2.6 Borehole information and aquifer properties

- *Borehole information*

The distribution of boreholes drilled in western Kammanassie Mountains is shown in Fig. 6-3. Little groundwater exploration has been done in the eastern part of the study area due to the difficult access and scarcity of detailed field geology survey. Some of the production boreholes are privately owned. The information on the production boreholes and the monitoring boreholes are listed in Table 6-2 and Table 6-3 respectively. The depths of these boreholes vary from 50m to 250m, and the drilling mostly ended at such depth where a main water-striking fracture is intercepted. Among them boreholes VR6, VR7, VR8 and VR11 are the only ones drilled on the outcrop of Peninsula Formation and constitute the Vermaaks River Wellfield; the rest are drilled on the outcrop of Nardouw Subgroup. From the geological logging it can be concluded that almost all the water strikes are associated with fractures and usually occur below the depth of 100m. Higher blow yields occur at deeper portions in most of the boreholes, which indicates that the highly conductive fractures could develop at a considerable depth. Because the deepest borehole in this area is only 250m, there is no evidence to identify the lower limit of depth where the fractures develop.

Table 6-2 Summary of the production boreholes data in the western Kammanassie Mountains (after Kotze, 2002)

Borehole	Depth (m)	Depth to Water Level (m)		Water Strike (m)*	Depth of pump (m)	Screen Depth (m)
		First	Now			
VG3	206.7	6.02	10	110-111(6.0), 190(3.0), 174 (3.0)	148	96.5-206.7
VR6	250	34.64	60	228-244(15)	165	108.7-230
VR7	177	63.3	90	78-81(8), 129-140(15)	159	53-177
VR8	251.3	100.5	125.4	113-117(5) 156-170(4) 234-240(4)	163	89.6-251.3
VR11	224.5	125.5	151	139(2) 183-194(8) 200-210(10)	180	18-224.5
DP10	210	114.07	90.2	183(7)	180	73-210
DP12	192	126.07	102.8	?(20)	180	66-192
DP29	240	120.6	97.09	160-170(2) 185-?(2)		
DP28	246	117.8	94.57	122-124(1.5) 151-160(10) 195-210(11)	170	121-207
DP15	224.5	103.8	86.04	110(3) 169(7) 187(11)	180	50-207
DP25	203	104.9	83.5	109, 166,201	170	9-203
DG110	212	110.6	107.57	114-117(1.5) 137 200-203(6)	200	92-212
DP18	17	3.6	3.2	4.2-9(15)	14	2-9.4
Note: The first water strike (fracture zone) depth (m), followed by yield, e.g. 110 – 111(6.0).						

The pumping rates of the production boreholes have been adjusted five times from 1993 to 2000 due to the continuous lowering of the water level. This is probably attributed to the recommended rates is simply based on pump test analyses, which only focus on the capacity of the production boreholes but discard consideration of the complexity of fractured rock aquifer. This usually leads to an overestimation of the supply potential. Fig. 6-16 shows the abstraction and water level fluctuation in the upper catchment of Vermaaks River with boreholes VR6, VR7, VR8 and VR11. It can be seen that the water level has been continuing to decline. The abstraction in 2003 is low because only the first three months' data are used. The recovered water level of year 1996 is because no abstraction was made in December of 1996.

Table 6-3 Summary of monitoring boreholes of the western Kammanassie Mountains (after Kotze, 2002)

Borehole	Depth (m)	Yield ($l \cdot s^{-1}$)	Geology	Depth to Water level (m)
WN101	243.5	>2.0	Baviaanskloof Quartzite, shale at 28m 188, 203 m, fractures at 120 m.	4.3 (1989)
VR5	215	15.0	0-12 boulders; 12-215 Baviaanskloof, shale at 37, 46, 57, 111 m, fractures at 82, 102, 169 and 184-186 m. *(75-215)*.	4.3 (1989)
VG12	173	4.7	0-4 boulders; 4-230 Tchando Formation, fractures at 19, 78, 98, 14 and 171-173 *(40-173)*	2.93 (1992)
VG4	113	<2.0	0-2 scree, 2-113 Baviaanskloof	18.2 (1989)
DG107	210	4.1	0-22 boulders, 20-210 Kouga Formation	27 (1987)
DG104	250	5.7	0-8 Enon, 8-250 Kouga Formation	90 (1987)
DP27	249	135-140 (2) 140-195 (10) 240(8)	0-22 Enon 22-249 Baviaanskloof Formation, Fractures at 150 to 155 m, open joints with showing weathering at 241, 242 and 248 m	119 (1992)
DP20	220	0.9	0-18 Enon, 18-220 Baviaanskloof Formation	104.5 (1991)
DP14	167	12	0-6 Enon, 2-30 weathered sandstone, 30 to 167 sandstone	62.5 (1986)
DP13	184.6	30	Baviaanskloof with shale	112 (1990)
G40171	50 (34-40)	?	0-17 boulders 17-50 Peninsula quarzite	5.085
G40172	16 (0-16)	(5.0)	Boulders	5.125
G40173	10 (0-10)	(3.0)	0-10 sandstone boulders and fragments in yellow sand matrix	4.925
G40174	147 (129-135)	127-133 (13)	0-12 sand and scree 92-147 sandstone and shale Fracture zone: 127 –133 with dark brown Fe staining	105.98
G40175	126	84(5.0)	0-23 Boulders 23-49 C/S layer 49-126 Peninsula quartzite	
G40175A	84 (57-63)	27 (11) 60(0.75)	0-19 Sand, boulders and scree 19-45 C/S layer 27-30 fractured with quartz vein 48-84 Quartzite, fractured, Fe stained, pyrite quartz veins	Artesian
G40176	150 (39-45) (116-122)		0-17 sand and boulders 17-150 sandstone and shale weathering visible up to 119 m, reddish to yellow brown stains	6.71
G40177	150	92(2.4)	0-17 Sand and boulders 17-150 Sandstone (water strike in quartz vein)	51.94
G40178	120 (51-57)	54(8.0)	0-11 weathered sandstone 11-120 sandstone 94-114 fault zone with quartz veins containing pyrite	10.22

A preliminary water balance was carried out for the Kammanassie Mountains by assuming that recharge is the only source to the system and spring flow and groundwater abstraction the only losses from the system. Taking into account the results of the water balance study, pumping test interpretation and the borehole characteristics, the total recommended yield of the Vermaaks River Wellfield was given as 1555 m^3/day (18 *l/s*), according to which three scenarios of pumping schedules were recommended on a continuous basis (Table 6-4). Of all the wellfields in Kammanassie Mountains, a total capacity of 1.27×10^6 m^3/year was estimated (Kotze, 2002). These scenarios will be simulated in the later sections.

Table 6-4 Pumping schedules for boreholes in Vermaaks River Wellfield

Borehole	Pumping Schedule (l/s)		
	Scenario 1	Scenario 2	Scenario 3
VR6	Monitor	Monitor	2
VR7	15	18	10
VR8	Monitor	Monitor	3
VR11	3	Monitor	3

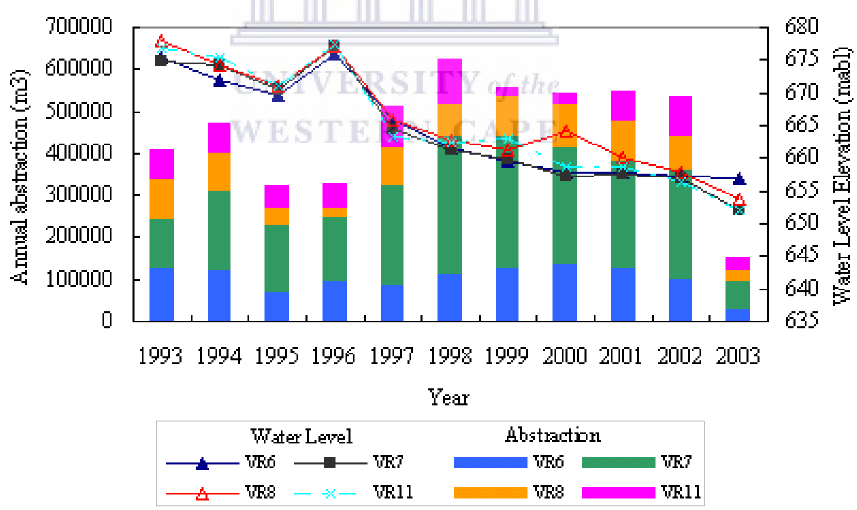


Fig. 6-16 Pumping rates and water level in upper Vermaaks River field (1993-2003)

- *Aquifer Properties*

The rock of the Peninsula Aquifer is of very low primary porosity due to the cementation of individual sand grains and later recrystallisation. The secondary porosity is well developed through the high-frequency brittle fracturing during the latter deformation of the indurative rock. More silty and shale interbeds appear in the Nardouw Subgroup together with high feldspar content, which have a great impact on the fracturing and folding style of Nardouw Aquifers. The storativity varies a lot with spatial differences.

The secondary porosity of the fault zone in the Vermaaks area was estimated up to 5%, even as high as 7% (Hälbich and Greef, 1995). Wu (2005) thought these figures were overestimated by the illustrational fracture model and the value in a range of 0.5~2% was more reasonable. This range is used in this study.

The transmissivity (T) and storativity (S) in the Vermaaks River Wellfield estimated in KKRWSS are listed in Table 6-5. These values are adopted to derive the initial parameter values in numerical modeling and then calibrated in the later section of this chapter.

Table 6-5 Ranges of transmissivity and storativity in Vermaaks River Wellfield

Conditions	$\mathbf{T}_{min}$($m^2 \cdot d^{-1}$)	$\mathbf{T}_{max}$($m^2 \cdot d^{-1}$)	$\mathbf{T}_{aver.}$ ($m^2 \cdot d^{-1}$)	$\mathbf{S}_{min}$	$\mathbf{S}_{max}$	$\mathbf{S}_{aver.}$
Extreme	7	424	103.9	1.0E-3	2.2E-3	1.35E-3
Condition A	5	144	61.25	1.0E-3	2.2E-3	1.08E-3
Condition B	29	424	191.72	1.0E-3	2.2E-3	1.08E-3
Condition C	17	276	178.92	1.0E-3	2.2E-3	1.08E-3
Condition D	7	161	90.86	1.0E-3	2.2E-3	1.08E-3
Condition E	7	161	90.86	1.0E-3	2.2E-3	1.96E-3

6.2.7 Groundwater level

A simplified groundwater piezometric contour map for the western Kammanassie Mountains (Fig. 6-17) is interpolated from the rest water level data of the existing boreholes using Kriging interpolation technique. This map can only provide a general over view of the water level condition due to the uneven distribution of boreholes. The generated groundwater level ranges from 350m to 910m. The general trend of groundwater flow is unexceptionably from the high-altitude area to the low elevation area, which coincides with the topography of this area. The groundwater flow in the Vermaaks River valley is along with the river flow direction. This can be attributed to the Vermaaks River Fault that acts as local flow boundary. The groundwater level map will be used as the initial hydraulic heads in the numeric modeling.

The groundwater levels of the production boreholes have been declining since the 1990s in the Vermaaks catchment (Fig. 6-18). However the abstraction has not been explicitly reflected in the monitoring boreholes except VG16. This may be attributed to the influence of the abstraction from the privately owned boreholes.

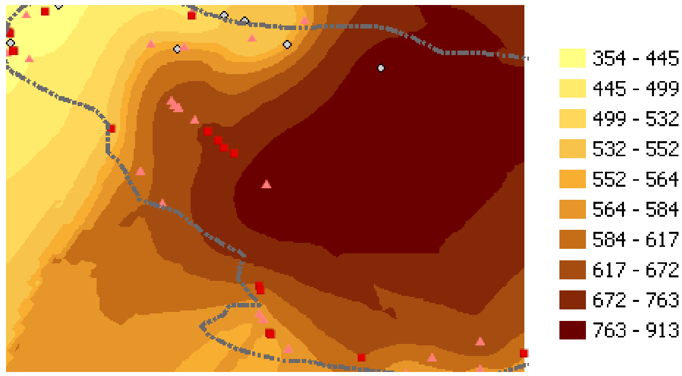


Fig. 6-17 Groundwater piezometric contour map of western Kammanassie Mountains

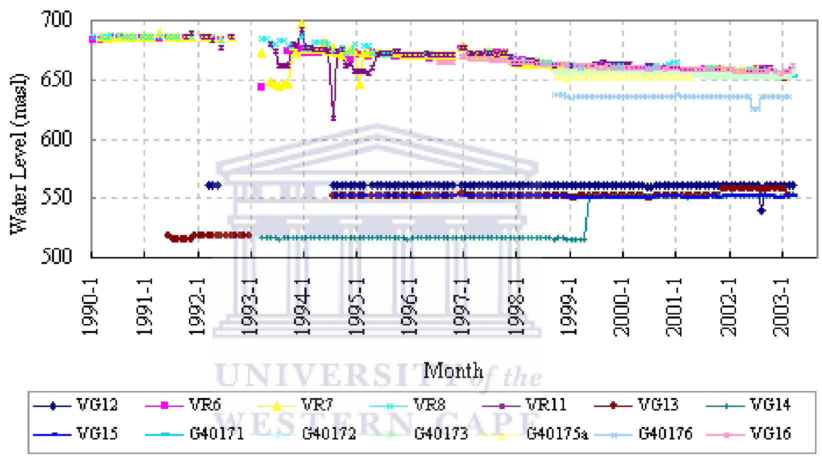


Fig. 6-18 Water level fluctuation in Vermaaks River Area

6.2.8 Groundwater quality

Kotze (2002) summarized that the groundwater in Kammanassie Mountains is characterized by low salinity (TDS<300mg/l), low pH (<6) and low total alkalinity (0.5meq/l). Groundwater quality varies with the host aquifer formation and the recharge source. The Peninsula Aquifer is the highest yielding TMG Aquifer with the best groundwater quality, however, most of the Peninsula aquifers outcrop in the high altitudes of the mountain catchments. High yielding boreholes with good groundwater quality also occur in the Nardouw Aquifer inside a permeable aquizone, viz. Vermaaks Keystone Block, at lower altitudes.

6.2.9 Groundwater recharge

The groundwater recharge in Kammanassie Mountains has long been studied by from different researchers. However, as the recharge process in this fractured rock aquifers is very complex that cannot be measured accurately or calculated precisely by using an ideal model. As all of the previous estimations are based on various assumptions of the hydraulic boundary, homogeneous system or a simplified conceptual model, large differences in the results obtained by different researchers often occur even for the same study area. This is also the case in Kammanassie Mountains. A variety of methods and techniques have been used in Kammanassie area including CMB (Chloride Mass Balance), SVF (Saturated Volume Fluctuation), CRD (Cumulative Rainfall Departure), Baseflow, Carbon-14 dating, EV (Equal Volume), EARTH, GIS Raster, etc. Usually the recharge is represented by a percentage of rainfall. Based on the previous studies, Kotze (2002) calculated the recharge rate via the "RECHARGE" spreadsheet software developed by Xu and van Tonder (2000), yielding the recharge rate of 14% for Peninsula Aquifer and 5% for Nardouw Aquifer. However, Wu (2005) gave much lower estimation of about 1.65 to 3.30% in this area. Woodford (2001) applied a GIS raster approach to estimate the recharge in the upper catchment of Vermaaks River and the resulted in 3.8% as a mean value, 4.8% as maximum and 2.5% as the minimum, respectively. In deed the big differences in the groundwater recharge estimate for the Kammanassie area make further application very difficult in terms of groundwater resource evaluation. In the later section of this chapter, a numerical model will be set up and then the model will calibrate the recharge in the Vermaaks Window area.

6.3 Conceptual hydrogeological model of Kammanassie Mountains

6.3.1 An initial 3D model construction of Kammanassie Mountains

An ideal conceptual hydrogeological model for fractured rock aquifer should demonstrate the settings and fabrics of groundwater regimes and should present groundwater circulation behaviors under natural and artificial conditions. It usually requires basic information such as geological/structural data, fracture properties, and groundwater test and monitor results to build the hydrogeological model.

With 2D contour maps, for example, the mind must first build a conceptual model of the relief before any analysis can be made. Considering the cartographic complexity of some terrain, this can be an arduous task for even the most dextrous mind. 3D display, however, simulates spatial reality, thus allowing the viewer to more quickly recognize and understand changes in elevation.

3D model can create the virtual reality. It gives a perspective view from surface to subsurface of the earth, which is invisible on a 2D map and can make the spatial relationship between geological formations and groundwater circulation easy to be perceived. Moreover, spatial analysis is easy to perform with the aid of 3D model. Undoubtedly 3D models have much more advantages than a 2D model, especially for groundwater study. No true 3D subsurface models were available previously in the TMG area except some geological cross sections and surface models interpolated from the borehole logging data. This is because the construction of 3D model is difficult if some specific softwares, such as OpenGL technique, are usually unavailable. Another problem is that, usually the construction of 3D model is more dependent on the geological data than 2D model because the complicated topology relationship between the geological formations must be completely correct.

With a thick sequence of target formations buried below the ground, it is really necessary to build the 3D model in TMG area to reveal the groundwater storage and flow regime in the subsurface. In this study a tentative or initial 3D model was built for Kammanassie Mountains, which is the first 3D model in TMG area.

6.3.2 The process of the 3D model construction

Besides the borehole logging information, 16 cross sections have been done based on the geological studies of the area, to reveal the deeper aquifer which is dominated by the Table Mountain group. The Locations of these cross sections are plotted in Fig. 6-19.

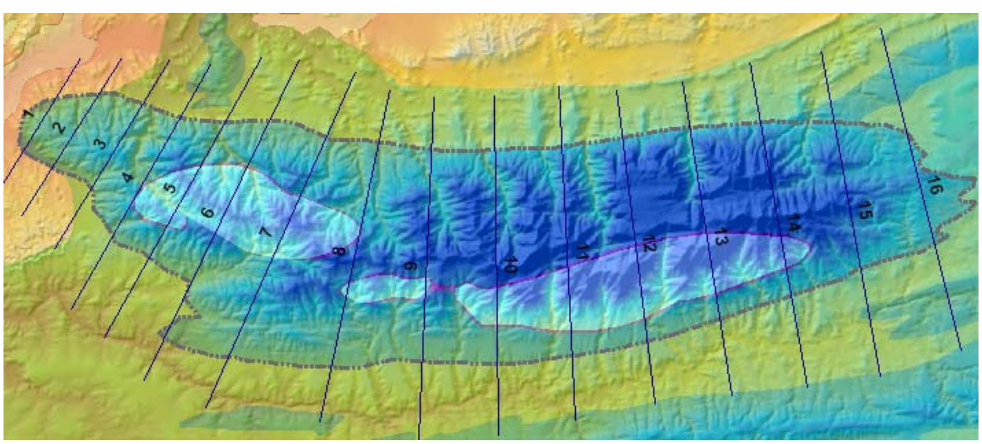


Fig. 6-19 Cross sections (1-16) of Kammanassie Mountains

The surface geological features and associated hydrogeological significance has been discussed in section 6.2. Some simple geological cross-sections were also adopted from other researchers to illustrate the general flow regime in the study area. Cross Sections 1-16 (Fig. 6-19) are considerably selected and are quasi-evenly distributed in the whole study area. The information from both geological map and topographical map, i.e. surface elevation, top and bottom elevation for specific formations, are captured for each cross section. These cross sections are then digitized in AutoCad. Thereafter the elevation data of each geological formation is captured manually for these cross sections and input to Excel, in which data are processed to be compatible with ArcGIS. With the 3D analyst extension and VBA programming of ArcGIS, the 3D model of Kammanassie Mountains can be constructed. The flow chart of the construction procedures is listed in Fig.6-20. The reality of a 3D model is much dependent on the adequacy of source data which have been captured. Therefore 3D model construction is a time-consuming job. Fortunately the results usually deserve the arduous work. It is expected that the 3D model can help to improve the understanding of conceptual hydrogeological model in the study area.

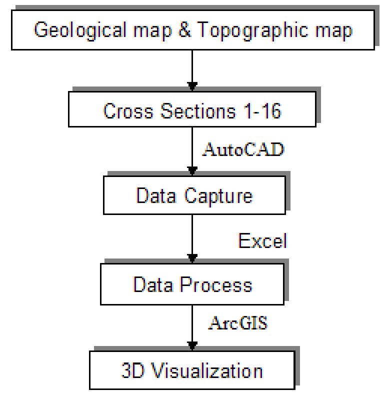


Fig. 6-20 Flow chart of the construction of the 3D model

6.3.3 3D visualization

Fig.6-21 is the Kammanassie Mountains 3D model displayed by the vertical exaggeration rate of 6. The left shows the distribution of these cross sections. It can be seen that the Kammanassie mega anticline is plunging both eastern and western and sticking up in the middle. The Peninsula Aquifer distributes along the mountain crests and comprises two thirds of the total thickness of the TMG (1800 m to 2150 m) and the outcrops of Peninsula Formation form the recharge areas. The Nardouw Aquifer with a thickness of 500-1000m distributes around Peninsula Aquifer and is compartmented by the Kammanassie mega anticline. Simply looking at the cross section 16 (Fig. 6-22), the eastmost cross-section in the study area, several structural compartments develop along this cross-section, separating the Nardouw Subgroup into four parts on the ground surface. Much more complicated characteristics and inhomogeneous recharge occur in the Nardouw Aquifer. The Cedarberg Formation is a shale layer of 50-120 m thick in the study area and missed in the Vermaaks River fault zone. It forms an aquitard between the Peninsula and Nardouw aquifers.

The figure on the right in Fig. 6-21 presents a whole picture of the study area that incorporates both the surface topography and the subsurface stratigraphic configuration. The DEM distinctly shows the surface hydrogeological features. Tributary streams develop from the mountainous area and flow northward to the Olifants River or southward to the Kammanassie River respectively. Considering the surface topography and the stratigraphy, groundwater is expected to occur at lower locations. However, so far no borehole could reach the deep buried TMG groundwater in the wide river valley areas, which are usually much deeper than 500m, and there is no more convincible evidence of the biggest groundwater circulation depth except some inferences from the exiting hot springs and conceptual models. Groundwater exploitation is still limited to the local or intermediate regime, usually targeting at strongly fractured zones along the faults. The contact zone between the target aquifer (TMG) and adjacent aquitard (Cedarberg Formation or Bokkeveld Formations) is another common choice in borehole siting.

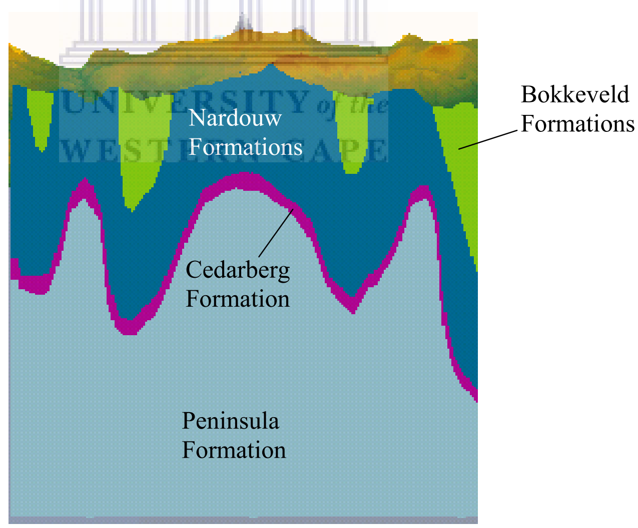


Fig. 6-22 Cross Section 16 on the east of Kammanassie Mountains

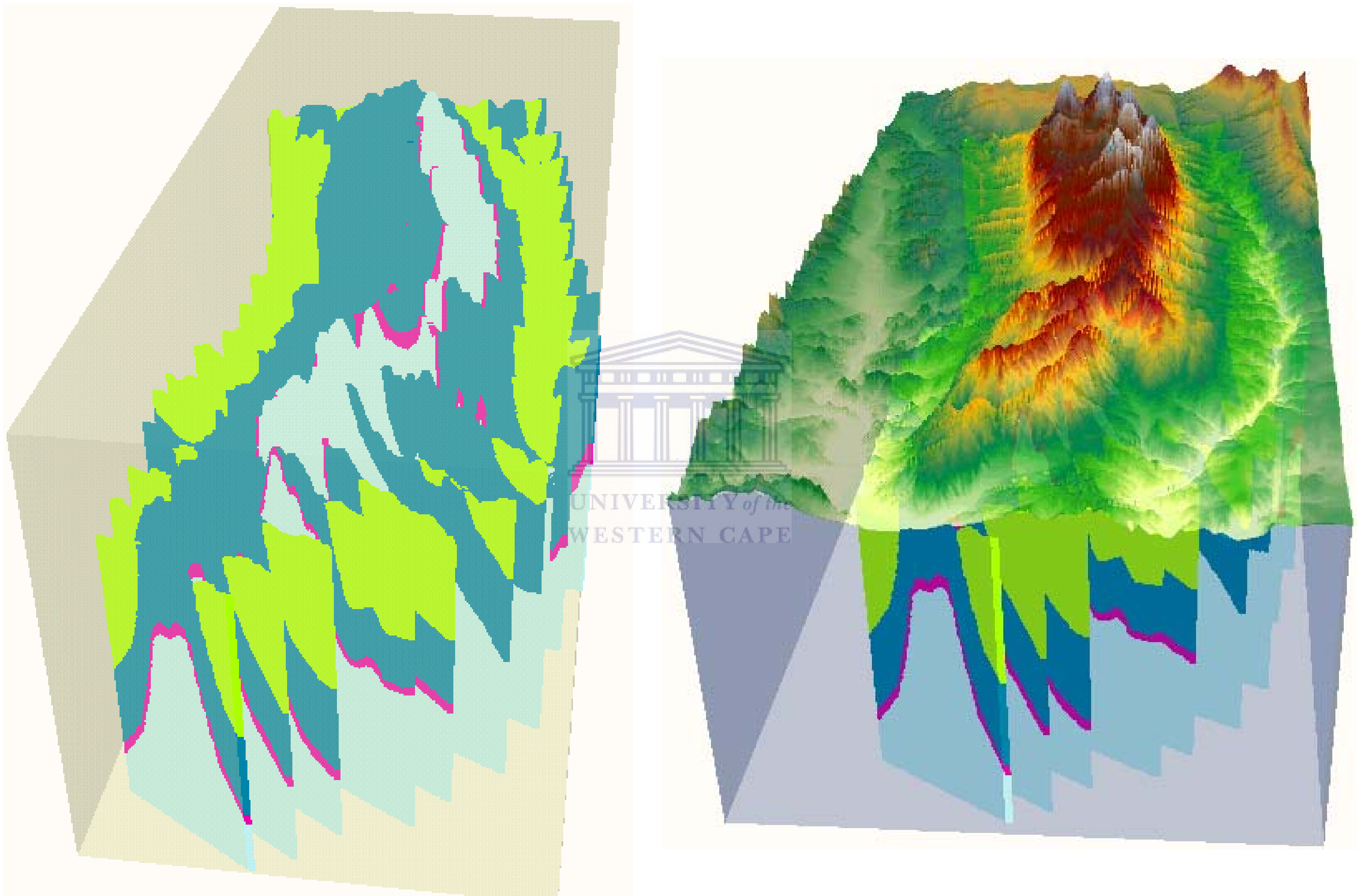


Fig. 6-21 3D model of Kammanassie Mountains. Left: Distribution of cross sections 1-16; Right: Dem overlying on the cross sections

6.3.4 Regional groundwater flow regime

Due to the deficient borehole data, the regional groundwater flow can only be assumed, using a schematic section to illustrate the postulated regional groundwater flow directions in Klein Karoo area. The Cango fault in the north of Kammanassie Mountains (Fig. 6-1) is usually regarded as the impervious boundary for the regional flow and groundwater recharge via Swartberg Mountains is assumed to flow to the Karoo area in the north. The groundwater flow direction is in accordance with the configuration of Peninsula aquifer, which is elevated in the mountainous area and depressed sharply in the intermountain area where Bokkeveld Group outcropped. Further research is needed to verify the postulation of regional flow by providing more convincible evidences of the facticity of the flow, or the magnitude of the fluxes and depth.

6.3.5 Intermediate groundwater flow regime and local groundwater flow regime

Combined the 3D model with water levels in boreholes, the intermediate groundwater flow regime and local regime could be preliminarily described. On an intermediate scale, like Kammanassie Mountains, groundwater recharge mainly takes place in the higher altitude areas (recharge areas), where more precipitation occurs. Recharge areas include Peninsula outcrop areas and part of the Nardouw outcrop areas. Groundwater recharge reaches the groundwater storage through fracture networks and there is accordingly an infiltration zone between groundwater level and the surface. Because the direct infiltration, the groundwater level in the recharge areas is higher and then flows to the lower altitude areas. A postulation made here is that the lower limit of intermediate groundwater flow depth is in accordance with the hydrological system on the same scale, which means that the intermediate flow regime is between the groundwater level in recharge areas and the water stages in the adjacent Olifants River and Kammanassie River. This postulation coincides with the borehole water level distribution in this area and is not contradictory with previous inferences (Wu ,2005), as showed in Fig. 6-13. According to the postulation, 350m a.s.l., the lowest water stage of the two rivers in the study area, is assumed to be the lower limit of intermediate groundwater flow based on the river stage derived from DEM. The upper flow limit is deduced from the borehole water level as about 1000m a.s.l. Therefore the intermediate groundwater flow regime is within 1000m a.s.l. to 350m a.s.l., and groundwater flows from the high-altitude mountainous areas to the low-altitude river valleys, which accords with the surface topography but smoother.

Vermaaks Window area is regarded as a local flow regime according to the surface geological evidence and borehole water level distribution. Though the groundwater flow in Vermaaks Window area may be impacted by surface topographical features, the control action of the hydraulic boundary of Cedarberg Aquitard and Vermaaks River Fault is hydrogeologically prevailing. Due to the usually limited area of local flow regime, the abovementioned postulation in intermediate flow regime is not applicable on this scale. In Vermaaks Window area, the lowest altitude is about 680m at the Vermaaks River mouth to the outside of the area according to the DEM, however the water level in the boreholes (VR6, VR7, VR8, VR11) is lower than that after abstraction. Ultimately the local flow regime of Vermaaks Window area is determined by both the objectives of the study and the information of boreholes. With a combined consideration the flow regime is determined as between the lowest of 400m a.s.l. and the highest water level in the recharge areas, which can be initially set from the DEM and then calibrated in the numerical modeling.

6.4 Groundwater flow modeling

Since the local flow regime has been determined and the initial values of model parameters could be extracted from the borehole data in Vermaaks Window area, the numeric groundwater flow model is set up for this area. First the past conditions are configured to calibrate the model parameters and then, the calibrated parameters are introduced into the model to predict the aquifer response to the recommended pumping scenarios. The water budgets associated with the modeling scenarios are expected to explain the basic groundwater resource allocation in this area. To simplify the problem, the assumption is made that the aquifer is a continuous porous medium and the fracture networks are averaged in an equivalent isotropic hydraulic conductivity. The Cedarberg Aquitard is modeled as groundwater flow boundary, which is surrounding the modeling area except where the fault occurs. The groundwater flow is simulated on steady-state in PMWIN (Chiang and Kinzelbach, 2001).

6.4.1 Model configuration and preprocess

6.4.1.1 Model configuration

The modeling area is showed in Fig. 6-23. The size of the rectangle area is 14000 (west-east) by 6500m (north-south) or 91km^2. The active area is about 47.34km^2. The rectangle area is discretized into square grids with 140 columns and 65 rows, as shown in Fig. 6-24. After several model trials with different settings of model layers, only one layer is involved and modeled as confined/unconfined (Type 3) with varied transmissivity. Both transmissivity and storage coefficient are set as "calculated" rather than "user specified" considering the uncertainties of the variation of water levels. The top elevation of the layer is derived from the DEM and the bottom is set to be at the lower limit of the local flow regime, viz. 400m a.s.l.

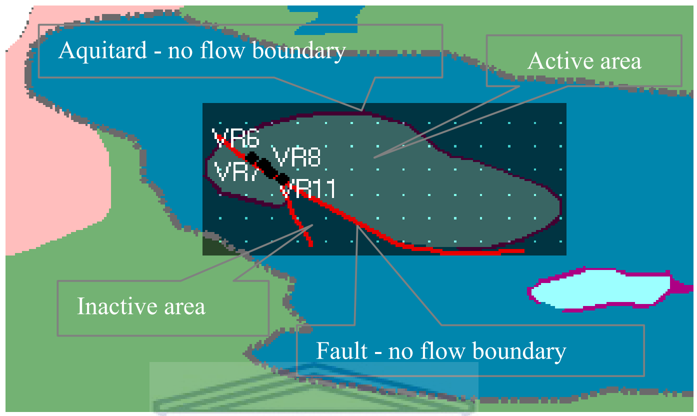


Fig. 6-23 Modeling area of Vermaaks Window

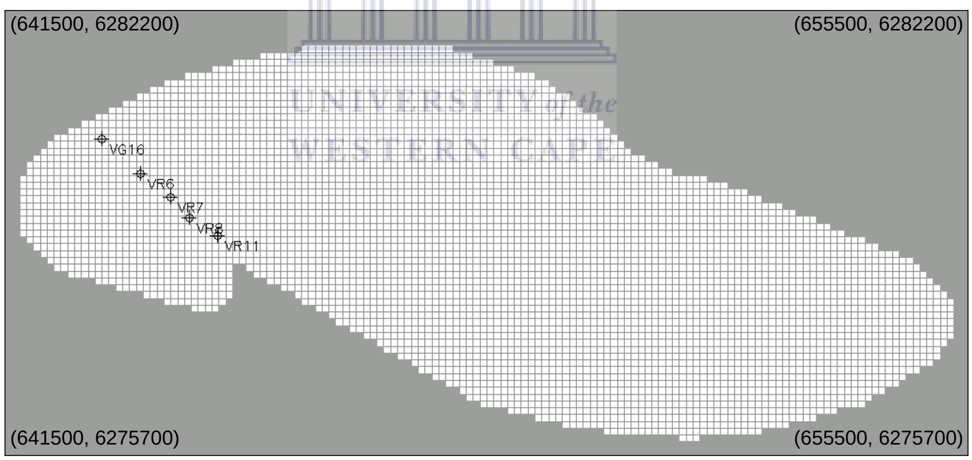


Fig. 6-24 Model grid in PMWIN and observation boreholes
(Coordination System is WGS_1984_UTM_Zone_34S)

The interaction between Vermaaks River groundwater has not been modeled with the RIVER Package, because only the upper reaches of Vermaaks River is included in the modeling area, which is ephemeral. According to the borehole water level (652~656m a.s.l.) and the elevation of the riverbed (minimum of 675m a.s.l.) derived from the DEM, it can be assumed that Vermaaks River has no direct hydraulic interaction with the main groundwater system that we presently study, so do the other rivers occur in the area. These intermittent rivers mainly interact with the shallow water in the weathered zone (see Fig. 6-9), besides, infiltration may occur through the riverbed that contributes to the groundwater storage.

Averagely recharge rate for the whole year is imposed with RECHARGE Package since there is not a distinctive bimodal seasonal cycle of rainfall in this area. Four zones of groundwater abstraction standing for the working boreholes VR6, VR7, VR8 and VR11 are imposed using WELL Package. The past 10 years (starting of 1993 to end of 2002) actual pumping rates are modeled, from which the parameters could be calibrated, and then new parameters are used to model the planned scenarios.

6.4.1.2 Data preprocess

Most of the data preprocess was done in ArcGIS and Excel and automated with VBA programming, including discretization and assigning parameters. All the programming scripts are self-compiled. With the spatial and topology function of GIS the used-to-be burdensome preprocess work for modeling becomes easier and interesting. The procedures are described in the following steps:

Step 1. Determination of model area in GIS

A pre-estimated size of the model area is required, and then the number of the columns and rows of the grids that will be used for modeling could be designed, after which a rectangle polygon covering the model area with definite coordination was created as shape file in ArcMap.

Step 2. Discretization of the model area in GIS

The well-designed polygon in step1 will be discretized using a VBA script, named“DividePolygonForFreeSize” in ArcMAP. When the user selects a polygon that needs to be discretized using a selection tool, then press the button that linked to the script (as showed in Fig. 6-25). Two input boxes will prompt to require the user to input the number of columns and rows for the selected polygon. Then the discretization process will be implemented. As GIS deals with the topology, thereby is superior to some other plotting softwares. It may take longer to get the discretization result for large areas with denser grids.

Actually it is very easy to achieve this step directly in PMWIN. However, the reason why we do it in GIS is that the powerful spatial function in GIS may be used to evaluate the parameters for each cell precisely and easily, which is usually difficult to do in PMWIN.

Step 3. Determination of the row and column number for each grid in GIS

The discretized grids in step 2 have nothing to do with MODFLOW if these grids are not indexed with the number of column and row. Initially this was intended to be incorporated into step2. However it was found that more time would spend than doing it separately because the number of rows and columns vary with during the discretization. Therefore another script, named “CalculateColAndRow”, based on the topology relationship of these grids was created to index the grids. The sequence of numbers was designed to coincide with MODFLOW, in which the number of columns increases from left to right, and the number of rows from top to bottom. Two fields named “Column” and “Row” will be added to the attribute table with the corresponding number for each grid.

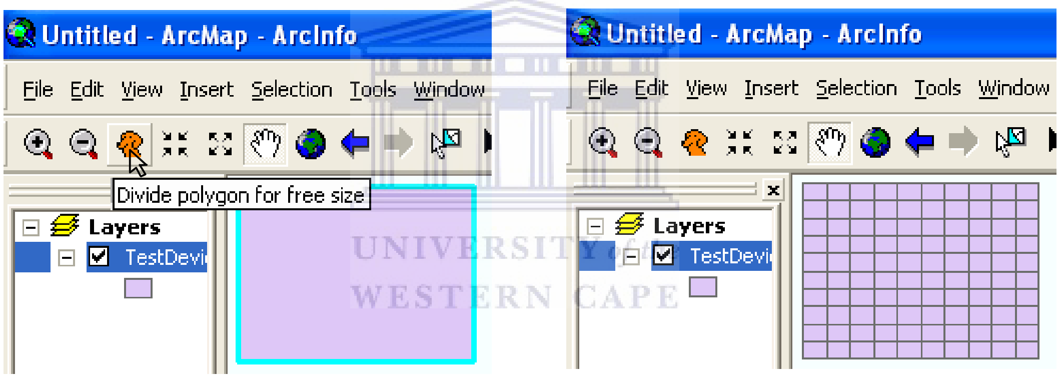


Fig. 6-25 Automatical Discretization of model area in ArcMap
Left: Polygon preparation, Right: Discretization result (10 Rows by 10Columns)

Step 4. Setting elevations in GIS

A script named “ExtractValueToPolygon” was compiled aiming to extract surface elevation values for each grid from the DEM of modeling area. Bottom elevations for each layer can also be extracted if a raster file of the bottom elevation is available. This is usually associated with very well studied areas. Two ways of extraction are considered, one is that the elevation value at the center of each grid is extracted to represent for the elevation of the grid, the other one is that the elevation values are extracted for the four angle points of the grid and then averaged to transfer to the grid. The second way may have more accuracy with the cost of fourfold of processing time compared to the first one.

Step 5. Assigning parameter value in GIS

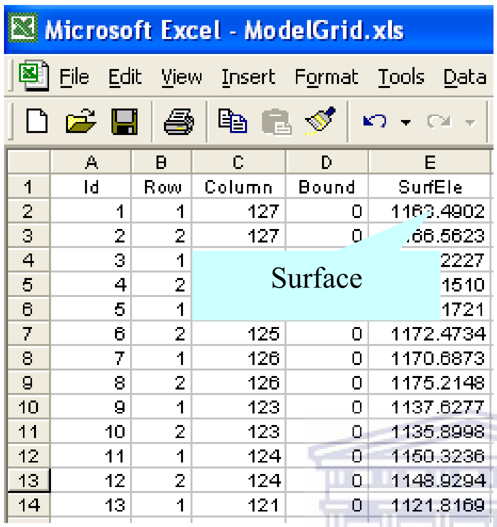
Almost all the model parameters can be assigned in GIS including boundary conditions, top and bottom elevation for each layer, initial hydraulic heads, aquifer properties. Also data can be prepared in GIS for different packages. Before setting the parameters, open the attribute table of the shape file and add all the necessary fields that will store the parameter values, like “Boundary”, “River”, “Well” and others. The length needs to be decided and significance decimal bit also needs to be set for a double precision number. Make sure they are in accordance with the values that going to be stored. The most frequently used function in this step is the spatial selection, which is embedded with ArcMap and powerful. Take the present modeling area as example, the active cells, inactive cells or fix-head cells can be decided using a series of spatial selection. Using spatial selection, the cells located on the Peninsula Formation are easily selected and a buffer zone with user-determining distance is optional to include those cells located in the contact zone of Peninsula and Cedarberg. The selected cells can be set “1”for the field “Boundary” to represent active cells. Other topological relationship can also be used to refine the selection step by step to finally in more complex cases. Other parameters with spatial variation that can be determined by spatial relationship with other datasets can also be set in this way. For the constant values, like effective porosity in this study, the most efficient way is to input directly in PMWIN use “Reset matrix” function.

Some data cannot be prepared just by spatial selection and then assigning value, like wells. The WELL PACKAGE in MODFLOW requires the wells’ position (row and column), pumping layers and pumping rate for each layer. The spatial selection can only deal with the first one. The second two can be managed in step 6.

Step 6. Preparation of input files for PMWIN in Excel

If all the spatial parameter values for each cell have been assigned in GIS, the attribute table of the target shape file can be exported as a dbf file or text file and then open the dbf or text file in Excel. It is noted that if the cells are over than 66536(the maximum rows for Excel) In such case Microsoft Access should be selected as the processing software. A VBA script named “TransferData” in Excel was compiled to transfer the cells into the MODFLOW compatible format for each parameter. Fig. 6-26 shows an example of the data format before and after the transfer. The transferred data range can be selected and then saved as Text (Tab delimited data) file with the specified name. Any grid-related parameter can be processed in this way.

As to other data like well, as mentioned in the previous step, only the column and row number can be decided in GIS. They can be separately processed. First, calculate the pumping rate of each well for each modeling layer. Then use another data transfer script "TransferData2" to transfer the wells into the MODFLOW compatible format for each layer. All other values are "0" except the well-located cells where the pumping rate is not 0 after the transfer.



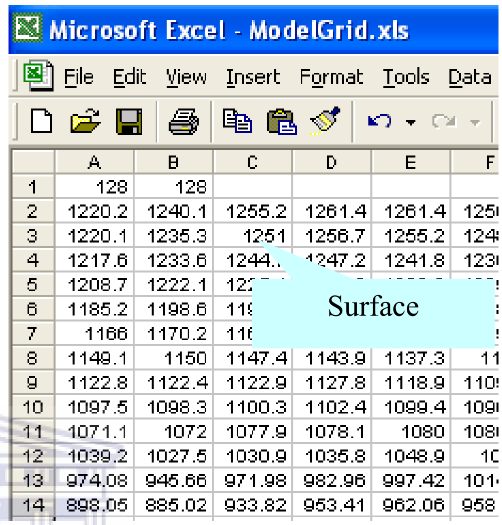


Fig. 6-26 Data transferred from the GIS attribute table data to PMWIN compatible format. Left: Original data; Right: Data after the transfer

After all the data are converted to the MODFLOW compatible format, open PMWIN, and almost all the parameter setting can be done by "Value→Matrix→Load…". Then in the file browse window select the Text file that saves the current parameter for the grids. The parameter values will be assigned to each grid. This method is going to be modified to include the local refinement function of the grids, just like what can be done in PMWIN. The new script is ongoing.

The flow chart of the data preprocess for groundwater flow modeling is showed in Fig. 6-27. Some of the procedures are also applicable to other works. The discretization of polygon has been applied in the study of the fracture connectivity combined with other scripts compiled in ArcGIS.

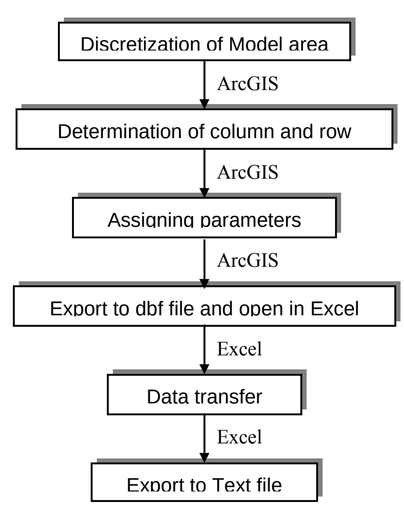


Fig. 6-27 Flow chart of the data preprocess for groundwater flow modeling

6.4.2 Model Parameters and inputs

- *Aquifer Parameters*

The model layer of type 3 with varied transmissivity in MODFLOW requires the following aquifer parameters to be specified: horizontal hydraulic conductivity, specific storage (for transient-state simulation), effective porosity and specific yield (for transient-state simulation). Based on the ranges of Table 6-5 and other sources (Woodford, 2002), the initial values are decided and input to the model, as listed in Table 6-6. The associated Min and Max values are used as lower limit and upper limit in model calibration.

Table 6-6 Initial Aquifer Parameter values

Aquifer Parameter	Initial Value	Min	Max
Horizontal hydraulic conductivity (m/s)	8×10^{-7}	1.0×10^{-8}	1.0×10^{-5}
Horizontal hydraulic conductivity (m/s) (Vermaaks River Fault zone)	8×10^{-6}	1.0×10^{-8}	1.0×10^{-5}
Specific storage	5.5×10^{-6} (m^{-1})	1.0×10^{-7}	1.0×10^{-5}
Effective porosity	2‰		
Specific yield	2‰	0.1‰	5‰

- *Recharge*

As mentioned in section 6.2.7, recharge estimations vary a lot among different researchers. The exiting recharge estimation values and the modeling values for Vermamaks Window area are listed in Table 6-7. The estimated recharge rates range between 1.65% and 14% in the modeling area. Considering the higher altitude of the Peninsula outcrops the MAP in this area is about 600mm, which is higher than what has been showed by Fig. 6-4. Therefore according to the existing estimation Vermaaks Window area receives groundwater on a magnitude of 0.4752×10^6 m^3 to 4.032×10^6 m^3 every year. Recharge is another model parameter that is calibrated by the model.

Table 6-7 The exiting recharge estimation values and the modeling values for Vermamaks Windows area

Area (km^2)	MAP (mm)	Type		Recharge				Ref.
				Rate	(mm/yr)	(10^6m^3/yr)	(m/sec)	
48	600	Existing estimation	Min	1.65%	9.9	0.48	3.14×10^{-10}	Wu (2005)
			Max	14%	84	4.03	2.66×10^{-9}	Kotze (2002)
		Numerical model	Initial	0.05	30	0.3	9.51×10^{-10}	
			Min	0.05%	3.15	1.44	1.00×10^{-10}	

			Max	15.77%	94.61	4.54	3.00×10^{-9}	

- *Abstraction*

Abstractions from the existing four boreholes are modeled using WELL package in MODFLOW. At first the past 10-year pumping conditions (from the start of 1993 to the end of 2002) listed in Table 6-8 were modeled with the water level at the end of the modeling period as observations. The borehole abstractions are calculated based on the pumping conditions, as shown in Table 6-9. To make the modeling simplified yearly abstractions (Mm^3/yr) are averaged to mm/s though the abstraction may be different from month to month. It is assumed that a long span of 10 years could reduce the seasonal variation.

Table 6-8 Pumping conditions and associated water levels of the boreholes for the past ten years (1993-2002)

Year	**VR6**			**VR7**			**VR8**			**VR11**			**Total abstraction**
	Abstraction		Water level	Abstraction		Water level	Abstraction		Water level	Abstraction		Water level	
	(m^3/yr)	(*l/s*)	(masl)	(m^3/yr)	(*l/sec*)	(masl)	(m^3/yr)	(*l/sec*)	(masl)	(m^3/yr)	(*l/s*)	(masl)	(*l/s*)
1993	127794	4.052	675.3	116539	3.695	674.69	94066	2.983	678	71485	2.267	676.7	12.997
1994	122688	3.89	671.9	187577	5.948	674.3	90351	2.865	674.35	71851	2.278	675.32	14.981
1995	65816	2.087	669.6	161723	5.128	670.4	39894	1.265	671.1	55610	1.763	671.2	10.243
1996	95475	3.027	675.89	152159	4.825	677.19	23515	0.746	677.15	54251	1.72	677.28	10.318
1997	84958	2.694	665.78	237528	7.532	664.34	90673	2.875	665.76	97133	3.08	663.2	16.181
1998	111903	3.548	661.5	328435	10.415	661.22	75459	2.393	662.82	108883	3.453	662.4	19.809
1999	125411	3.977	659.43	312134	9.898	659.68	96305	3.054	661.13	22864	0.725	663.12	17.654
2000	134199	4.255	657.83	279441	8.861	657.16	102850	3.261	664.14	25271	0.801	658.74	17.178
2001	124284	3.941	657.82	256745	8.141	657.53	96626	3.064	660.12	69303	2.198	658.68	17.344
2002	97826	3.102	657.11	262673	8.329	656.88	79823	2.531	657.75	93007	2.949	656.32	16.911

Table 6-9 Borehole abstractions of in the modeling area for the years 1993 to 2002 (Unit: m3/s)

No	**Column**	**Row**	**1993**	**1994**	**1995**	**1996**	**1997**
VR6	20	24	-4.0523E-03	-3.8904E-03	-2.0870E-03	-3.0275E-03	-2.6940E-03
VR7	24	28	-3.6954E-03	-5.9480E-03	-5.1282E-03	-4.8249E-03	-7.5320E-03
VR8	27	31	-2.9828E-03	-2.8650E-03	-1.2650E-03	-7.4566E-04	-2.8752E-03
VR11	31	33	-2.2668E-03	-2.2784E-03	-1.7634E-03	-1.7203E-03	-3.0801E-03
No	**Column**	**Row**	**1998**	**1999**	**2000**	**2001**	**2002**
VR6	20	24	-3.5484E-03	-3.9768E-03	-4.2554E-03	-3.9410E-03	-3.1020E-03
VR7	24	28	-1.0415E-02	-9.8977E-03	-8.8610E-03	-8.1413E-03	-8.3293E-03
VR8	27	31	-2.3928E-03	-3.0538E-03	-3.2614E-03	-3.0640E-03	-2.5312E-03
VR11	31	33	-3.4527E-03	-7.2501E-04	-8.0134E-04	-2.1976E-03	-2.9492E-03

- *Boundary conditions*

It is assumed that under natural condition, the inflow to the system is rainfall percolation to the groundwater table (recharge) and the outflow from the system is groundwater discharge from the spring (spring 051) located on the west boundary, as shown in Fig. 6-17. A constant head boundary may be assigned to the grid where the spring is located in a natural steady-state simulation. However, as we know from the observed data, spring 051 has dried up since the groundwater level has been declining with the pumping. Thereby in the simulation of a pumping condition in this area (transient state simulation), spring 051 could not be assumed as constant head boundary. Under such condition the outflow from the system is the well abstraction. Also, from the distribution of initial heads it may be inferred that the east boundary of the modeling area is the furthest from the pumping zone, thereby is hardly influenced by the abstraction. The imposition of the no flow boundary around the modeling area is based on the assumption that the groundwater flow system in the modeling area is relatively independent, which simplifies the modeling by overlooking the indirect river leakage and groundwater interchange with the outside of the model. With the consideration of these factors, a general head boundary is specified on the east boundary of the modeling area to allow for the communication between the local groundwater flow system and the outside. The hydraulic head on the boundary is specified as the initial head and the hydraulic conductance can be calibrated by inverse model.

- *Time*

Ten time periods are used to simulate 10 years (1993 to 2002) and 12 steps representing 12 months are included in each period in the model calibration process. Both the steady-state and transient-state were simulated and finally it is decided that steady-state is more applicable to the modeling area because of a relatively evenly recharge and yearly abstraction. Model for prediction is also simulated for 10 years.

- *Initial hydraulic heads*

Though the actual hydraulic heads usually are not prerequisite in MODFLOW for steady-state but for transient-state flow simulation, to improve the facticity of the numerical model, we try to simulate the actual condition. However, actual hydraulic heads are often not available and interpolated from the borehole levels. In the modeling area only several boreholes were drilled and distributed along the Vermaaks River valley, which couldn't not be interpolated for the whole area. Therefore a pre-model run on a steady-state was executed for 5 years to simulate the pre-pumping condition. Initial hydraulic heads for the pre-model were derived from DEM except the borehole water levels. The rest borehole water levels before 1993 were used and specified as constant heads. No abstraction and recharge were imposed intending to simulate the natural-balance state. The resulted hydraulic heads of the pre-model (Fig. 6-28) are assumed to be the initial hydraulic heads (Fig. 6-4) for the formal model.

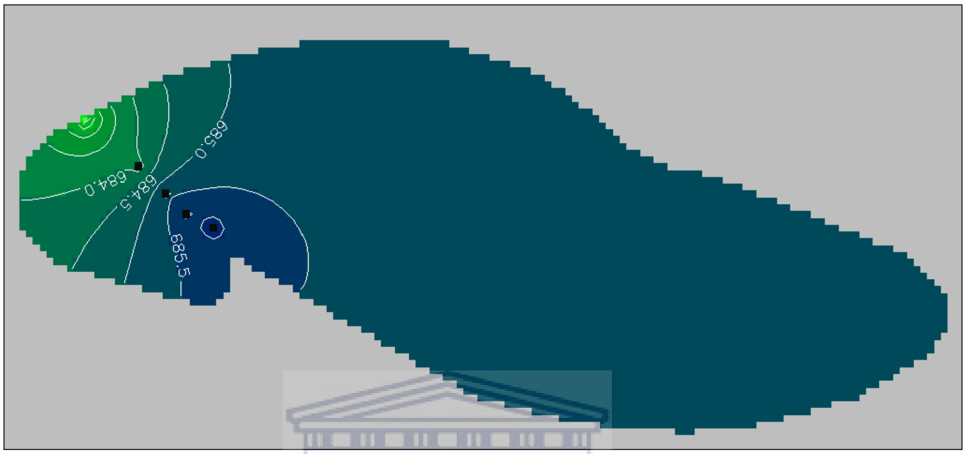


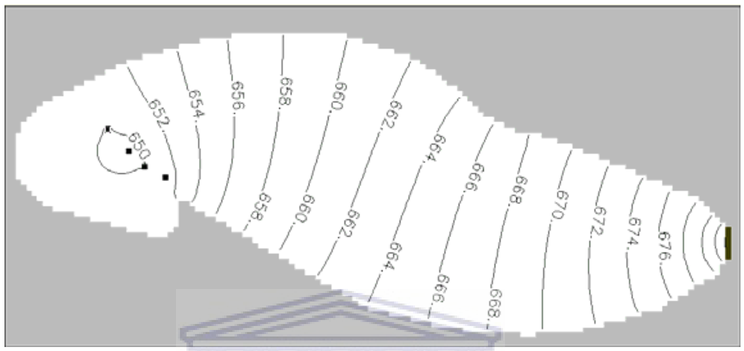
Fig. 6-28 Initial hydraulic heads in the modeling area

- *Boreholes and observations*

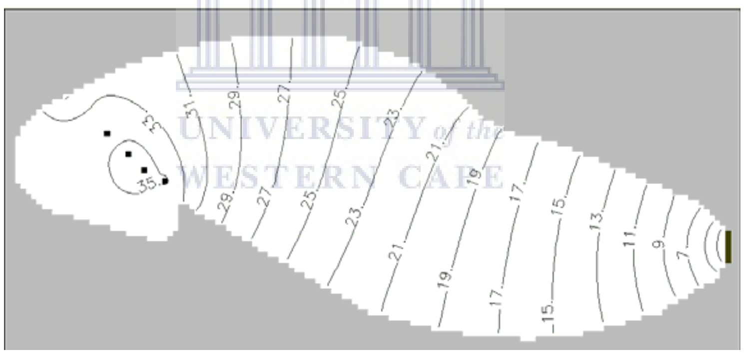
This option is especially for the calibration process. Besides the four pumping boreholes, another borehole VG16 is served as monitoring hole and has been monitored on a regular basis. Therefore the water level data of VG16 are available during the modeling periods. The water levels of the four pumping boreholes are also introduced as the observations. Finally the monitored water levels of the five boreholes in the end of 2002 are used as observations. Their coordinates and corresponding hydraulic heads are input for the model calibration. The location of the observation boreholes is showed in Fig. 6-24.

6.4.3 Model Calibration

Model calibration is carried out by inverse model PEST (Doherty et al., 1994) which is incorporated in PMWIN. Because the steady-state simulation type is selected, only two parameters, namely Recharge and Horizontal hydraulic conductivity, are calibrated in the inverse model. Their initial values, and possible range (minimum and maximum values) has been given in Table 6-6 and Table 6-7 respectively. Table 6-10 listed the simulated water level on the observation wells, and the difference between the simulated and observed values are given as well. It can be observed that the simulated water level is generally lower than the observed ones, except VR11. Calibrated parameter values and are shown in Table 6-11 with the 95% confidence interval. The estimated hydraulic conductivity and the hydraulic conductance of the General Head Boundary are all higher than the initial value, but the calibrated recharge is much lower than the initial one. The contour maps of simulated hydraulic heads and drawdown in December of 2002 using calibrated model parameters are showed in Fig. 6-29 (a) and (b) respectively.



(a) Simulated hydraulic heads in 2002.12



(b) Simulated drawdown in 2002.12

Fig. 6-29 Result contour map of pumping scenario1

Table 6-10 The comparison of measured water level and simulated water level in Dec, 2002

Borehole	Initial WL (masl)	Observed Result WL (masl)	Simulated Result WL (masl)	Error (m)
VG16	683	656.450	653.031	3.419
VR6	683.66	654.400	652.196	2.204
VR7	685.60	653.870	651.642	2.228
VR8	686.20	654.820	652.689	2.131
VR11	686.50	652.270	653.731	-1.461

Table 6-11 Calibrated model parameters and their confidence limits

Model Parameters	Initial Value	Estimated Value	95% percent confidence limits	
			Lower limit	Upper limit
Recharge (m/s)	9.5×10^{-10}	5.01×10^{-11}	2.366046×10^{-11}	1.056615×10^{-10}
Hydraulic conductivity (m/s)	8×10^{-7}	7.2×10^{-6}	5.111307×10^{-6}	1.013505×10^{-5}
Hydraulic conductivity (m/s) Vermaaks River Fault Zone	8×10^{-6}	1×10^{-5}	3.616345×10^{-6}	2.361634×10^{-5}
GHB Hydraulic Conductance (m^2/s)	2.9×10^{-4}	2.69×10^{-3}	1.872598×10^{-6}	3.86708×10^{-1}

It's a little surprising that the calibrated recharge of 5.01×10^{-11} m/s is extremely low compared with the previous estimations. It is equivalent to 0.27% of the MAP (600mm) and the annual recharge volume amounts to about 77200m^3. The water budget shows that only 14% of the abstraction (out flow) is balanced by recharge (in flow) whilst 86% of it by the head dependent boundary, accounting for the continuously declining water level and the exploitation induced recharge.

The calibrated recharge could not necessarily be regarded as the actual recharge that takes place in this area because there are a number of assumptions which may simplify the system and introduce the inaccuracy to the model. However, this estimate basically provides a magnitude of recharge for the Peninsula groundwater in this area.

Most of the previous estimates are crosschecked and it is found that the different demarcation of the flow regime may account for the large variety of the estimations. The estimation given by Kotze (2002) was an averaged value of all the previous results obtained from different methods, ranging from soil method, baseflow to hydrochemistry approaches, etc. In another word the flow regime defined in different methods may range from the weathered zone to the intermediate groundwater circulation system. Usually if the flow regime is limited to the saturated zone, the recharge estimation only considers the infiltration that reaches the groundwater storage, therefore is small. The estimation in this study and those used hydrochemistry methods fall in this case. On the other hand, if the flow regime is not only including the saturated zone but also the shallow unsaturated zone, the recharge estimation is relatively high. Baseflow method, earth model, soil method, and etc fall in this case.

According to the water level in the boreholes, the groundwater abstraction in the modeling area is obviously from the saturated groundwater storage. Therefore the estimation of recharge should be accordingly made only for the saturated zone to ensure the proper evaluation of sustainable yield of the aquifer through these boreholes. Based on the above discussion and an integrated consideration with the previous estimation, the author recommend that the Peninsula groundwater recharge should be in the range of 0.2% to 2% of the rainfall, which amounts to about 57600 ~ 576000m^3 per year or in the consistent unit of borehole yield, 1.83 to 18.3*l/s*. Actually the upper limit of this range is still too high because the groundwater level has declined for about 30 meters with an continuous abstraction rate less than 18 *l/s* (average 15.36 *l/s*, ranging from 10.2-19.8 *l/s*) in the years of 1993 ~ 2002 (see Table 6-7). From this point, the groundwater of Peninsula Window area has been overexploited with the pumping rate near the upper limit of the recharge rate. The sustainable yield of the Vermaaks River Wellfield should be much lower than that value.

6.4.4 Model prediction and sustainable yield of model area

The calibrated model parameters are used in the model prediction for another 10 years from 2003 to 2012. Firstly the three scenarios of pumping schedule listed in Table 6-3 are simulated and then the pumping rate of the existing boreholes are calibrated by the inverse model Pest.

Fig. 6-30 ~ Fig. 6-32 shows the contour map of simulated hydraulic heads and drawdown of the three scenarios. Because the whole pumping rate keeps the same (18 *l/s*) in all the scenarios, the general distributions of the hydraulic heads and the drawdown are similar to each other. The averaged drawdown of the modeling area is about 22.9 m, which is also the same in each scenario. It's indubitable that a 10-year-drawdown on this level will induce a lot of problems including the insufficient water supply, deterioration of borehole efficiency, negative environmental impacts, and so on. Therefore the sustainable yield of the borehole is simulated inversely using the previously calibrated parameters with the given drawdown in the 5 boreholes (VG16, VR6~VR11) as constraints. According to the pumping test, VR7 is the most efficient borehole of the four in Vermaaks Wellfield; therefore it is assumed that the abstraction is from the single borehole VR7. Three levels of drawdown (1m, 5m, 10m) in the 5 observation boreholes induced by the pumping in VR7 are simulated to derive the optimized pumping rate of VR7 for each drawdown level, after which the optimized values are modified to be integer values and then the groundwater flow are simulated directly with the integer value of pumping rate. The optimized pumping rate of VR7 and the relevant integral values together with the resultant averaged drawdown of the direct model are listed in Table 6-12.

Table 6-12 Drawdown and pumping rate of VR7

Observation Drawdown[1)] (m)	Pumping Rate (l/s)		Averaged Drawdown[4)] (m)
	Optimized[2)]	Integer[3)]	
1	2.26	2	0.045
5	4.23	4	2.758
10	6.61	7	6.980

Notes:

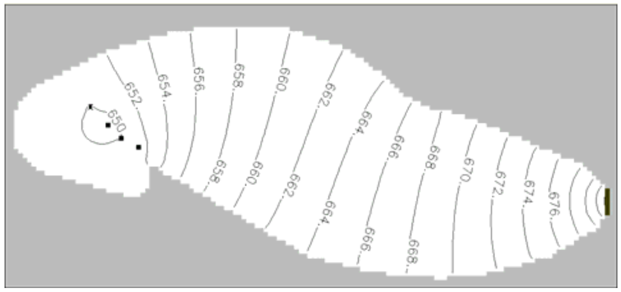
1) Observation Drawdown: the drawdown is input into the inverse model as observation values;

2) Optimized: the optimized pumping rate of borehole VR7 from the inverse model;

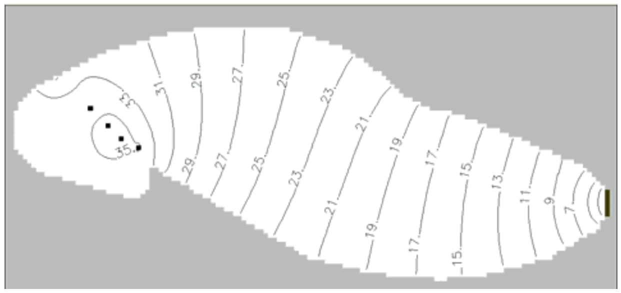
3) Integer: the integral value of the optimized pumping rate of borehole VR7;

4) Averaged Drawdown: the averaged drawdown in the modeling area derived from the direct model using the integral pumping rate values.

Fig. 6-33 ~ Fig. 6-35 shows the contour map of simulated hydraulic heads and drawdown of the direct model with the integer pumping rates of VR7. As can be seen clearly, if the pumping rate is 2*l/s*, the averaged drawdown of the model area is close to 0 after 10 years' abstraction. Therefore the sustainable yield should be 2 *l/s* or a little higher than that, i.e. 2.4 *l/s*, equaling to the recharge rate in this area on a continuously pumping basis. The pumping rate of 4 *l/s* will probably lead to an averaged drawdown of 2.758m after 10 years, which may not cause serious problems as described before. Comparing with current pumping rate of the wellfield, the pumping rate of 7 *l/s* still appears acceptable, although it may result in a dangerous situation with averaged drawdown of 7m and more than 10 m in the capture zone. In a long-term operation, cautions should be taken in such conditions, like slowing down the pumping or stopping it for some time for the recovery of groundwater level.

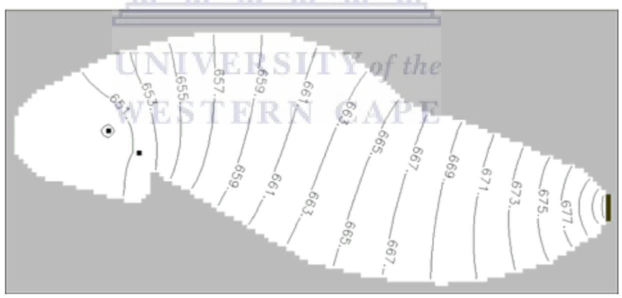


(a) Simulated hydraulic heads in 2012.12

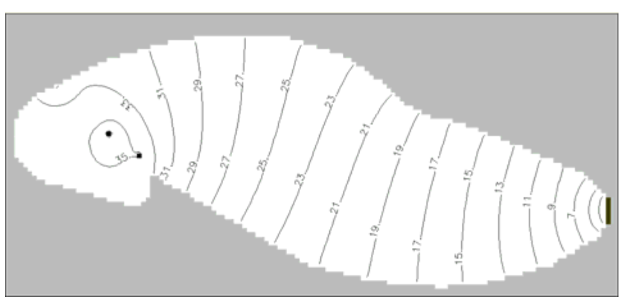


(b) Simulated drawdown in 2012.12

Fig. 6-30 Result contour map of pumping scenario1



(a) Simulated hydraulic heads in 2002.12



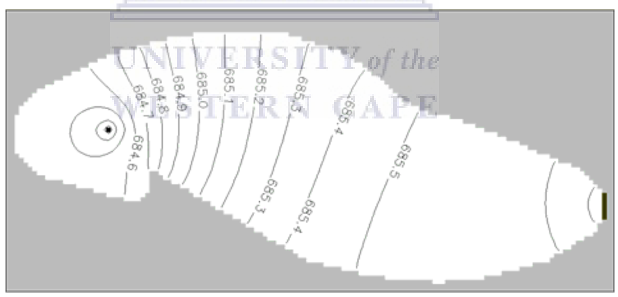
(b) Simulated drawdown in 2002.12

Fig. 6-31 Result contour map of pumping scenario2

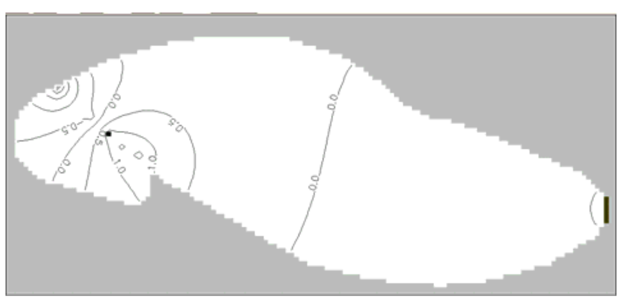
(a) Simulated hydraulic heads in 2012.12

(b) Simulated drawdown in 2012.12

Fig. 6-32 Result contour map of pumping scenario3

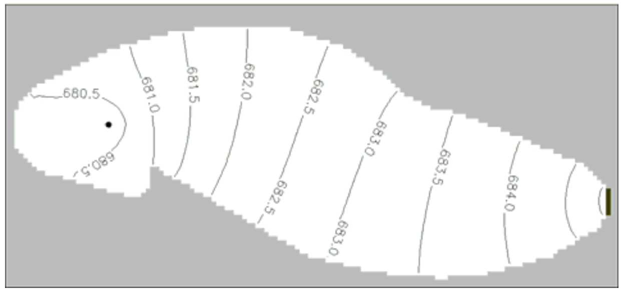


(a) Simulated hydraulic heads in 2012.12

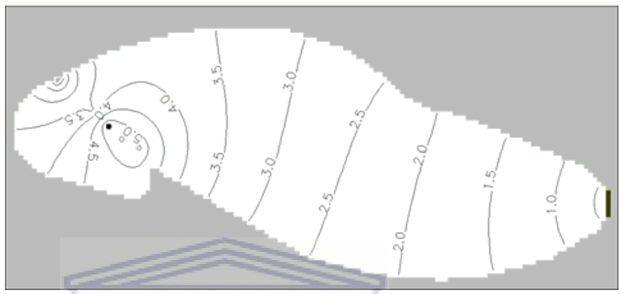


(b) Simulated drawdown in 2012.12

Fig. 6-33 Result contour map of the groundwater flow simulation from 2003.1 to 2012.12
(Pumping Rate=2 *l/s*, Averaged Drawdown=0.045m)

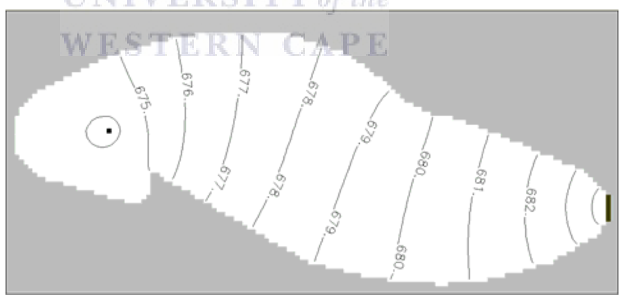


(a) Simulated hydraulic heads in 2012.12

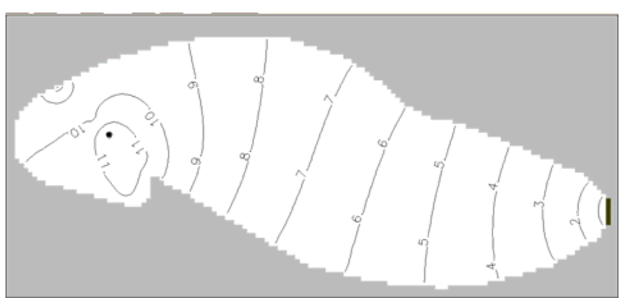


(b) Simulated drawdown in 2012.12

Fig. 6-34 Result contour map of the groundwater flow simulation from 2003.1 to 2012.12 (Pumping Rate=5 *l/s*, Averaged Drawdown=2.758m)



(a) Simulated hydraulic heads in 2012.12



(b) Simulated drawdown in 2012.12

Fig. 6-35 Result contour map of the groundwater flow simulation from 2003.1 to 2012.12 (Pumping Rate=7 *l/s*, Averaged Drawdown=6.980m)

6.5 Summary

Kammanassie Mountains is located in the eastern section of the Klein Karoo area and has been part of the KKRWSS. Kammanassie Mountains has a total surface area of 630km^2, comprising 120km^2 of Peninsula Formation outcrops forming three windows areas, 495km^2 of Nardouw Subgroup and 15km^2 of Cedarberg Formation in between. Groundwater abstraction is mainly carried out in the west part of Kammanassie Mountains and has experienced a long history from the 1980s up to present. Due to the incomplete understanding of the conceptual hydrogeological model and inaccurate estimate of the water balance calculation, the pumping schedule has been adjusted from time to time and groundwater level has declined continuously in Vermaaks River catchment.

Data analysis and evaluation is performed based on the previous studies. The 3D model of Kammanassie Mountains is constructed, which helps to improve the understanding of conceptual hydrogeological model. Regional, intermediate and local groundwater regimes are postulated respectively with the combined consideration of the hotsprings, water level and borehole information in the study area. The demarcation of flow regimes needs to be verified by further research and investigation.

The whole study area is identified as an intermediate groundwater flow regime with the contact between Nardouw and neighboring Bokkeveld Group acting as flow boundaries. Three local flow regimes are defined in the window areas mainly with the boundaries of Cedarberg Shale, which usually serves as Aquitard between Peninsula and Nardouw Aquifer.

One of the Peninsula window areas, Vermaaks River window is selected to simulate the groundwater flow in Peninsula Aquifer. Four production boreholes, namely VR6, VR7, VR8 and VR11, are located along Vermaaks River in the model area and all the groundwater abstraction in this area is made from them. Another borehole, VG16, is used as monitor borehole. With the regularly monitored water levels of the existing five boreholes it is possible to perform an inverse model first to calibrate the essential model parameters such as recharge, hydraulic conductivity, and etc. Therefore the past pumping period from January of 1993 to December of 2002 is modeled on steady state. An optimized recharge value of 0.26% of MAP is derived from the inverse model, and with the consideration of the previous estimation. The groundwater recharge in Vermaaks Window is estimated in the range of 0.2~2% of the MAP, equaling to 1.8mm to 18mm.

With the optimized model parameters from the inverse model, direct models are run in different scenarios of pumping schedule proposed by Kotze (2002) for the period from beginning of 2003 to the end of 2012. The same whole yield, 18 *l/s*, but different allocation to each borehole is simulated in the three scenarios. The results show that the average drawdown (22.9m) is almost the same in the three scenarios, which may lead to a series of problems.

Another three inverse models are carried out aiming to simulate the proper abstraction rate or sustainable yield by setting different drawdown levels (1m, 5m and 10m) of the five boreholes as observations at the end of the modeling period. VR7 is assumed to be the only pumping borehole as it is the most efficient among the four production holes. The optimized pumping results are 2.26 *l/s*, 4.23 *l/s* and 6.61 *l/s* with regard to the drawdown of 1m, 5m and 10m respectively.

At last 2 *l/s*, 4 *l/s* and 7 *l/s* as three levels of pumping are simulated again in direct model, resulting in three levels of average drawdown, i.e. 0.045m, 2.76m and 6.98m. The model results imply the sustainable yield in the Vermaaks River wellfield may be 2.0 l/s or could be a little higher, 2.4 *l/s,* without notable lowering of groundwater level. Practically, the water abstraction rate of 7 *l/s* still seems acceptable if the borehole operation can stop or slow down for some time for the recovery of water level.

Though the groundwater modeling reasonably simulated the groundwater level decline resulting from over abstraction in Vermaaks Window area, the model results should be used in coordination with the results or analysis of other methods, such as pumping test, water balance calculation, etc. This is because many conditions have been simplified in the modeling, e.g. the heterogeneous of fractured rock aquifer is simplified as homogeneous of porous aquifer, which may introduce errors to the model results. The groundwater monitoring should be insistent in order to verify the modeling results.

7. Conclusions and recommendations

The Table Mountain Group has been identified as a major regional aquifer system extending from Western Cape to Eastern Cape in South Africa and comprising a thick sequence of hard sedimentary rocks dominated by fractured sandstones with a thickness ranging from 900 m to 5000 m. The extensive distribution and the heterogeneity aroused by the highly fractured characteristics of TMG aquifer makes the groundwater resource evaluation of TMG more complicated. As the groundwater development in the TMG area is extremely uneven, of which most of the water use is concentrated in the western portion of the aquifer systems, the diverse evolutions of the groundwater in terms of quantity and quality have posed great impacts on the natural environments by wellfield operations. Therefore a proper regional groundwater resource evaluation, focusing on the quantification and dynamic relationship of recharge, discharge and storage, is of most importance for the efficient groundwater utilization and management of TMG aquifers.

A preliminary regional assessment of this resource involving the quantification of recharge, discharge and storage is carried out in this study and based on the quantification, a regional sustainable yield is proposed, intending to build a solid foundation for the future study. In the mean time, some applicable approaches dealing with data processing are also developed in this study, which could be contributed to the analog studies.

7.1 Regional groundwater resource evaluation of TMG aquifers

So far there are only some rough estimates on the groundwater resource of TMG aquifers on a regional basis. An assessment on this resource is very necessary for the proper utilization and management of it. Based on previous researches and existing data, groundwater recharge, storage and discharge of TMG aquifers are quantitatively evaluated. Sustainable yield is initially put forward according to the groundwater budget.

Groundwater recharge potential is estimated using soil water balance approach and the calculated result is soil water surplus, which can be regarded as the upper limit of recharge. The calculated total soil water surplus or the upper limit of recharge volume is about 4.36×10^9 m^3 per annum, and the mean annual soil water surplus in TMG outcrop area is 115.38 mm. The estimation of Wu (2005) is used as a calibration of the current result in this study.

The isobaths and isopachs are generated for the whole TMG area, which is used for the storage capacity estimation of TMG aquifers. The storativity values are generalized from the previous studies, and three scenarios, i.e. low, medium and high, are suggested for Peninsula Aquifer and Nardouw Aquifer respectively. The total groundwater storage capacity is estimated as 3.3×10^{10} m^3 with the medium storativity values. By taking into account the current technical feasibility of groundwater exploitation in the TMG aquifers, the usable storage capacity is evaluated with three scenarios presented by the exploitation depth of aquifers of 250m 350m and 500m, the amount of the storage capacity is 250m 350m and 500m, the amount of the storage capacity is 1.3×10^9 m^3, 2.1×10^9 m^3 and 3.4×10^9 m^3 respectively. Available storage capacity is estimated as 8.06×10^8 m^3, which stands for the storage capacity of the unsaturated zone.

A sum of 1.29×10^9 m^3/yr is estimated as the groundwater discharge from TMG aquifers, in which baseflow is separated from the stream flow data, and accounts for the biggest part of TMG groundwater discharge.

A primary groundwater budget is carried out and it is considered that the inflows and outflows are balanced with the consideration of possible imprecision. A sustainable yield of no more than 1.0×10^9 m^3/year (or <35515 l/s) is proposed for the groundwater exploitation of TMG aquifers based on the groundwater budget. The existing exploitation could be expanded properly.

7.2 Groundwater and surface water interaction in TMG aquifers

As the most common type of groundwater/surface water interaction in TMG area, stream-aquifer interaction is quantitatively analyzed for the TMG-related hydrological catchments. A digital recursive filtering method is adopted to separate the baseflow component from the monthly streamflow data, in which parameters are adjusted according to the hydrogeological characteristics of TMG aquifers. A total of 1.08×10^9 m^3 /yr is derived as the upper limit of the TMG groundwater discharge via streams considering the occurrence of interflow and the hydrodynamic changes of the interaction of groundwater and surface water. The results are summarized by quaternary catchments for the convenience of study.

The baseflow recession analysis is also carried out on a quaternary catchment G40A. The groundwater recharge and discharge could be estimated by this way. Unfortunately because of the relatively high data requirements, this analysis could not be extended to the whole TMG area.

7.3 The response of TMG aquifer to pumping in Kammanassie Mountains

The response of TMG aquifer to pumping in Kammanassie Mountains is studied by groundwater flow modeling. The Kammanassie Mountains is located in the eastern section of the Klein Karoo area and has been part of the KKRWSS. Due to the incomplete understanding of the conceptual hydrogeological model and inaccurate water balance calculation, the groundwater off the Kammassie wellfield has been overexploited and pumping schedule has been adjusted 5 times to compensate for the continuous lowering of water level in Vermaaks River catchment. Based on the existing data, including hydrogeological setting, rainfall and river flow, borehole and monitoring and abstraction data, Vermaaks River wellfield is selected to simulate the groundwater flow in Peninsula Aquifer. An inverse model is carried out first to calibrate the essential model parameters such as recharge, hydraulic conductivity, and etc from which an optimized recharge value of 0.26% of MAP is derived from the inverse model. With the consideration of the previous estimation, the groundwater recharge in Vermaaks Window is estimated in the range of 0.2~2% of the MAP, equaling to 1.8mm to 18mm. Another inverse models are carried out aiming to simulate the proper abstraction rate or sustainable yield by setting different drawdown levels. The model results imply that the sustainable yield in Vermaaks River wellfield may be 2.0 *l/s*. The model results also indicate that the implementation of higher pumping rate to the Vermaaks River wellfield can cause the lowering of groundwater level. Thus the overabstraction should consider the rest of the aquifer for the recovery of water level in a long-term operation.

7.4 Some general data processing approaches developed in the study

The vast distribution and highly fractured nature of TMG has posed a lot of problems to the study on it, like data collecting, statistics and analysis, which may consistutes some of the reasons of why there are few quantitative evaluation of this resource on a regional scale. The restrictions to the study may result from data deficiency, spatial variety, and difficulties in data processing, all of which could impede the sensible understanding of the hydrogeological model, and concequently, the reasonable assessment of the aquifer.

Most of the work in this study has been done in ArcGIS Desktop system. AutoCAD and Excel are also relied on to conduct part of the figure and data processing. Especially the second development with VBA (Visual Basic for Applications) embedded in these softwares has made a lot of impossibilities of the work into realities. Some genearl approaches, like 3D model construction and the data preprocessing for PMWIN are developed and can be applicable to other analog studies.

3D visualization is very difficult to be accomplished by the normal implementation in ArcGIS. Only the surface of the geological layers could be displayed as the DEM, which is called 2.5D – between 2D and 3D. With some scripts compiled with VBA, the true 3D model of the subsurface can be constructed and visualized to help to understand the conceptual hydrogeological model. It has been developed as a general approach and can be contributed to other studies.

Another approach is developed in the data preprocess for the groundwater modeling in PMWIN. GIS data are not compatiable with the present edition of PMWIN, which is inconvenient for the modeling since in most cases the spatial data are stored in GIS format. In this study some scripts are developed in ArcGIS, making the model discretization, boundary setting and parameter assignment be easily done with the spatial function and then be transferred to PMWIN through Excel. This approach successfully links GIS to MODFLOW, makes the groudnwater flow modeling much easier, especially in the procedure of data preprocessing.

7.5 Recommendations

The hydrogeological significance of TMG has been well acknowledged. A lot of groundwater researches associated with the TMG exploration and exploitation projects have been conducted, from which precious experiences in both theoretical and practical aspects are enriched, forming the foundation for the future works.

This study is carried out on the basis of the previous researches. Though a number of findings have been made that would contribute to the hydrogeological researches and groundwater sustainable utilisations in TMG area, there are still many aspects need to be further identified and improved in the future research. The important issues are listed as follows:

1) The methodologies used in the groundwater resource evaluation may be improved to be more adaptive to the TMG fractured rock aquifer system, including the definition and classification of groundwater resources, methods of investigations, management of the resource, dynamics of groundwater recharge, storage and discharge, transition between shallow groundwater and deep groundwater, determination of aquifer parameters, and groundwater dependent ecosystem, etc.

2) Comprehensive groundwater resource evaluation entails various approaches including both quantity and quality aspects, with a specific consideration of flow characteristics in fractured rock aquifers.

3) The continuous accumulation of basic data can always benefit a study. More case studies in TMG area should be conducted with a focus on the spatial distribution of the groundwater resource and flow charateristics. In addition, the groundwater monitoring network should be optimised, in conjunction with surface water monitoring if and where necessary, and focused on the water quantity, quality, water level, abstraction rate and etc.

4) The study of sustainable yield or sustainable yield is a primary concern for groundwater resource evaluation. As the estimation of sustainable yield can be based on the study of recharge, baseflow, numerical model or hydraulic test interpretation etc, it is recommended that these methods be jointly used for the applicable sustainable yield estimates, which are of significance in the scale of wellfield or water supply scheme. On the regional scale, the estimated sustainable yield results should be allocated to each basin for the convenience of water resource planning and management.

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Appendix 1

Mean annual surplus (MAS) from Soil water balance calculation for quaternary catchments of TMG outcrop areas

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
E10A	133.06	898.59	108.38	12.06%	14.42
E10B	166.61	736.31	145.85	19.81%	24.30
E10C	191.81	586.91	80.56	13.73%	15.45
E10D	234.62	518.44	62.76	12.11%	14.72
E10E	362.40	419.03	55.52	13.25%	20.12
E10F	385.82	406.98	54.42	13.37%	21.00
E10G	508.42	407.45	57.02	13.99%	28.99
E10H	162.16	494.87	69.14	13.97%	11.21
E10J	468.44	343.98	101.17	29.41%	47.39
E10K	191.83	283.59	46.59	16.43%	8.94
E21A	15.59	620.03	170.11	27.44%	2.65
E21D	105.02	626.57	134.22	21.42%	14.10
E21E	73.44	360.34	118.33	32.84%	8.69
E21F	50.17	288.89	132.00	45.69%	6.62
E21G	111.81	475.12	112.69	23.72%	12.60
E21H	404.25	428.52	102.67	23.96%	41.51
E21J	233.06	337.97	119.13	35.25%	27.77
E21K	265.36	351.89	104.82	29.79%	27.81
E22C	1.01	323.92	169.73	52.40%	0.17
E24A	236.86	392.57	113.76	28.98%	26.94
E24B	3.41	272.43	142.30	52.23%	0.48
E24J	357.20	235.18	113.18	48.12%	40.43
E24K	340.51	237.68	77.48	32.60%	26.38
E24L	459.04	310.58	106.30	34.23%	48.79
E24M	503.53	264.99	106.64	40.24%	53.70
E32E	233.79	192.60	68.18	35.40%	15.94
E33A	0.03	135.94	0.00	0.00%	0.00
E33B	6.45	113.90	0.00	0.00%	0.00
E33C	17.29	139.70	63.78	45.65%	1.10
E33F	156.03	212.30	94.53	44.53%	14.75
E33G	228.83	186.01	24.80	13.33%	5.67
E33H	197.08	133.77	0.00	0.00%	0.00
E40C	199.53	285.29	91.80	32.18%	18.32
E40D	494.43	284.26	104.54	36.78%	51.69
F60E	20.42	115.63	0.00	0.00%	0.00
G10A	129.61	1580.24	292.59	18.52%	37.92

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
G10B	119.39	1245.12	251.32	20.18%	30.00
G10C	41.45	1009.21	440.16	43.61%	18.25
G10D	9.11	625.39	392.87	62.82%	3.58
G10E	100.03	639.95	180.24	28.16%	18.03
G10F	19.66	514.65	239.74	46.58%	4.71
G10G	184.26	912.31	61.30	6.72%	11.29
G10H	28.60	411.34	170.56	41.46%	4.88
G10J	39.31	446.98	361.91	80.97%	14.23
G10K	271.50	381.85	151.23	39.60%	41.06
G10M	5.67	300.29	149.99	49.95%	0.85
G22A	236.68	683.68	320.05	46.81%	75.75
G22B	82.70	922.56	224.01	24.28%	18.53
G22C	9.90	605.43	349.61	57.75%	3.46
G22D	29.12	737.93	384.52	52.11%	11.20
G22F	36.84	1464.50	362.61	24.76%	13.36
G22H	4.51	669.23	588.94	88.00%	2.65
G22J	14.72	1002.14	741.78	74.02%	10.92
G22K	5.43	769.08	318.09	41.36%	1.73
G30A	331.33	259.70	86.40	33.27%	28.63
G30B	51.34	393.60	146.37	37.19%	7.51
G30C	327.93	409.52	112.01	27.35%	36.73
G30D	241.74	384.31	141.05	36.70%	34.10
G30E	331.32	248.55	65.20	26.23%	21.60
G30F	762.76	285.23	78.29	27.45%	59.72
G30G	603.79	252.96	71.94	28.44%	43.44
G30H	1068.31	213.96	29.73	13.90%	31.76
G40A	67.95	1120.50	203.64	18.17%	13.84
G40B	121.60	936.61	239.31	25.55%	29.10
G40C	142.60	1367.07	284.69	20.82%	40.60
G40D	327.00	983.80	231.50	23.53%	75.70
G40E	151.02	721.78	323.77	44.86%	48.89
G40F	28.14	515.27	285.87	55.48%	8.04
G40G	142.28	723.85	255.58	35.31%	36.36
G40H	90.55	697.83	217.80	31.21%	19.72
G40J	115.38	613.42	234.53	38.23%	27.06
G40K	33.47	495.81	220.21	44.41%	7.37
G40L	202.28	569.04	210.25	36.95%	42.53
G40M	322.68	573.53	175.82	30.66%	56.73
G50A	218.89	545.04	160.41	29.43%	35.11
G50B	203.99	531.07	176.91	33.31%	36.09
G50C	113.06	488.76	143.31	29.32%	16.20
G50D	108.21	431.43	176.48	40.91%	19.10

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
G50E	61.19	448.41	120.41	26.85%	7.37
G50F	62.02	453.14	152.02	33.55%	9.43
G50H	7.69	370.52	106.55	28.76%	0.82
G50K	63.84	440.63	0.00	0.00%	0.00
H10A	5.58	512.39	35.38	6.91%	0.20
H10B	112.73	707.75	154.71	21.86%	17.44
H10C	173.46	673.63	26.47	3.93%	4.59
H10D	96.78	1018.86	12.36	1.21%	1.20
H10E	81.61	1403.76	462.32	32.93%	37.73
H10F	125.48	783.69	170.07	21.70%	21.34
H10G	136.91	787.83	225.94	28.68%	30.93
H10H	79.63	885.81	26.09	2.95%	2.08
H10J	175.77	1594.86	488.48	30.63%	85.86
H10K	188.81	1224.84	586.83	47.91%	110.80
H10L	28.00	476.16	171.40	36.00%	4.80
H20A	24.20	357.14	105.37	29.50%	2.55
H20B	78.17	590.35	170.45	28.87%	13.32
H20C	58.87	642.96	67.20	10.45%	3.96
H20D	100.43	695.97	9.45	1.36%	0.95
H20E	94.49	906.39	280.47	30.94%	26.50
H20F	91.81	796.88	184.63	23.17%	16.95
H20G	55.86	680.13	142.40	20.94%	7.96
H30A	66.52	442.57	157.15	35.51%	10.45
H30B	70.59	374.37	66.46	17.75%	4.69
H30C	188.28	479.55	62.60	13.05%	11.79
H30D	52.13	385.11	77.91	20.23%	4.06
H30E	20.37	440.89	61.57	13.97%	1.25
H40A	87.92	426.20	87.65	20.57%	7.71
H40B	141.05	577.49	91.38	15.82%	12.89
H40C	37.38	374.92	82.70	22.06%	3.09
H40D	83.20	556.67	341.84	61.41%	28.44
H40E	110.40	539.13	393.97	73.08%	43.49
H40F	3.09	292.83	216.27	73.85%	0.67
H40G	102.30	416.95	239.14	57.35%	24.46
H40H	29.47	460.80	155.39	33.72%	4.58
H40J	38.85	416.95	106.42	25.52%	4.13
H40K	185.45	405.74	157.82	38.90%	29.27
H40L	9.46	381.32	114.67	30.07%	1.09
H50A	55.94	335.28	197.06	58.77%	11.02
H50B	30.07	389.23	4.79	1.23%	0.14
H60A	59.31	1894.50	527.01	27.82%	31.26
H60B	145.60	1126.69	335.95	29.82%	48.91

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
H60C	131.57	891.00	458.09	51.41%	60.27
H60D	104.33	651.84	222.85	34.19%	23.25
H60E	71.25	639.74	275.76	43.11%	19.65
H60F	81.03	581.64	210.79	36.24%	17.08
H60H	60.66	464.01	143.14	30.85%	8.68
H60J	102.08	457.44	182.95	39.99%	18.68
H60K	55.38	371.23	84.39	22.73%	4.67
H60L	19.97	360.76	86.17	23.89%	1.72
H70A	8.08	414.40	135.96	32.81%	1.10
H70B	35.30	694.37	161.53	23.26%	5.70
H70C	66.67	372.52	147.46	39.58%	9.83
H70D	99.29	634.75	87.73	13.82%	8.71
H70E	76.94	741.05	179.08	24.17%	13.78
H70F	6.54	573.22	231.64	40.41%	1.52
H70H	38.89	395.42	81.63	20.65%	3.18
H70K	38.52	458.42	42.31	9.23%	1.63
H80A	148.92	596.95	18.73	3.14%	2.79
H80B	78.37	791.68	206.14	26.04%	16.15
H80C	27.26	479.37	33.24	6.93%	0.91
H90A	125.09	644.68	61.66	9.56%	7.71
H90B	116.68	663.76	77.20	11.63%	9.01
H90C	18.37	466.68	95.06	20.37%	1.75
J11H	132.19	239.58	40.53	16.92%	5.36
J11J	151.34	303.70	12.35	4.07%	1.87
J11K	47.46	220.61	16.01	7.26%	0.76
J12A	94.21	436.97	142.88	32.70%	13.46
J12B	36.59	268.18	64.85	24.18%	2.37
J12D	35.60	289.31	117.98	40.78%	4.20
J12F	121.42	245.27	44.23	18.03%	5.37
J12G	72.30	276.66	62.47	22.58%	4.52
J12H	196.14	259.53	24.24	9.34%	4.75
J12J	75.52	250.03	34.97	13.99%	2.64
J12K	44.20	192.47	51.95	26.99%	2.30
J12L	110.59	314.06	131.89	42.00%	14.59
J12M	100.70	289.94	93.53	32.26%	9.42
J13A	96.29	295.24	29.37	9.95%	2.83
J13B	96.71	305.67	58.92	19.27%	5.70
J13C	78.97	350.51	82.73	23.60%	6.53
J23E	77.77	328.97	86.16	26.19%	6.70
J23F	66.10	194.23	70.65	36.38%	4.67
J23H	59.58	199.38	52.54	26.35%	3.13
J23J	128.66	307.70	49.03	15.93%	6.31

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
J24F	21.44	221.70	28.05	12.65%	0.60
J25A	266.73	288.59	50.04	17.34%	13.35
J25B	265.59	325.57	27.22	8.36%	7.23
J25C	159.62	288.13	16.11	5.59%	2.57
J25D	53.85	365.23	82.67	22.63%	4.45
J25E	159.51	244.46	51.82	21.20%	8.27
J31A	311.14	441.05	50.93	11.55%	15.85
J31B	112.65	359.19	83.65	23.29%	9.42
J31C	103.30	369.20	20.35	5.51%	2.10
J31D	31.07	299.98	18.06	6.02%	0.56
J32E	63.80	234.34	26.24	11.20%	1.67
J33A	173.77	392.53	78.51	20.00%	13.64
J33B	220.15	436.91	134.69	30.83%	29.65
J33C	98.83	292.90	56.44	19.27%	5.58
J33D	93.30	378.95	74.35	19.62%	6.94
J33E	115.94	445.73	81.81	18.35%	9.49
J33F	47.69	343.28	73.17	21.32%	3.49
J34A	220.05	476.51	97.36	20.43%	21.43
J34B	211.37	569.32	162.25	28.50%	34.30
J34C	243.29	673.55	252.89	37.55%	61.53
J34D	179.09	470.83	128.69	27.33%	23.05
J34E	120.72	426.68	138.52	32.47%	16.72
J34F	85.65	415.04	176.01	42.41%	15.07
J35A	96.55	418.28	102.62	24.53%	9.91
J35B	237.24	410.49	194.11	47.29%	46.05
J35C	181.80	373.04	101.97	27.34%	18.54
J35D	46.64	406.50	66.74	16.42%	3.11
J35E	29.52	269.88	53.89	19.97%	1.59
J35F	146.41	341.33	71.56	20.96%	10.48
J40A	237.58	417.88	74.72	17.88%	17.75
J40B	212.11	431.15	65.18	15.12%	13.82
J40C	211.16	521.32	81.53	15.64%	17.22
J40D	14.28	445.61	116.99	26.25%	1.67
K10C	115.86	492.70	66.23	13.44%	7.67
K10D	2.88	454.11	79.53	17.51%	0.23
K10E	88.58	679.30	86.44	12.72%	7.66
K10F	1.34	502.44	17.89	3.56%	0.02
K20A	62.73	721.97	83.17	11.52%	5.22
K30A	53.21	752.85	153.29	20.36%	8.16
K30B	39.84	787.16	93.40	11.86%	3.72
K30C	77.51	805.11	116.81	14.51%	9.05
K30D	87.23	724.31	97.40	13.45%	8.50

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
K40A	79.08	705.57	92.24	13.07%	7.29
K40B	70.91	845.63	117.90	13.94%	8.36
K40C	51.90	930.39	120.57	12.96%	6.26
K40D	16.64	756.73	85.93	11.36%	1.43
K40E	220.03	864.32	108.31	12.53%	23.83
K50A	235.46	849.64	115.42	13.58%	27.18
K50B	202.86	881.94	93.02	10.55%	18.87
K60A	161.46	663.86	156.90	23.63%	25.33
K60B	143.20	753.60	118.07	15.67%	16.91
K60C	160.85	744.43	110.30	14.82%	17.74
K60D	292.62	814.63	136.55	16.76%	39.96
K60E	98.53	774.54	72.57	9.37%	7.15
K60F	188.96	806.46	82.29	10.20%	15.55
K60G	125.18	860.00	87.11	10.13%	10.90
K70A	170.41	920.11	75.30	8.18%	12.83
K70B	106.50	997.24	77.12	7.73%	8.21
K80A	146.00	1029.50	82.14	7.98%	11.99
K80B	208.44	1031.08	99.49	9.65%	20.74
K80C	189.01	1016.84	105.71	10.40%	19.98
K80D	173.20	936.19	135.82	14.51%	23.52
K80E	245.38	894.73	202.54	22.64%	49.70
K80F	157.73	545.68	131.92	24.18%	20.81
K90A	213.81	716.15	168.52	23.53%	36.03
K90B	145.81	774.13	283.65	36.64%	41.36
K90C	255.45	596.31	128.44	21.54%	32.81
K90D	116.30	692.62	162.05	23.40%	18.85
K90E	54.77	676.22	148.76	22.00%	8.15
K90F	125.70	698.55	160.51	22.98%	20.18
K90G	152.97	653.85	124.04	18.97%	18.97
L30A	0.16	283.94	1.12	0.40%	0.00
L50A	41.29	294.71	43.51	14.76%	1.80
L70A	49.92	248.48	45.63	18.36%	2.28
L70B	0.05	236.33	14.02	5.93%	0.00
L70C	89.70	224.18	46.08	20.55%	4.13
L70D	33.37	252.52	37.08	14.69%	1.24
L70F	111.86	315.95	21.75	6.88%	2.43
L70G	445.24	503.87	57.50	11.41%	25.60
L81A	331.78	526.84	92.40	17.54%	30.66
L81B	261.41	427.84	58.51	13.67%	15.29
L81C	332.49	436.73	59.30	13.58%	19.72
L81D	308.12	393.02	61.58	15.67%	18.97
L82A	269.28	595.06	86.87	14.60%	23.39

Quaternary Catchment	Outcrop Area (Km^2)	Quaternary MAP (mm)	Outcrop_MAS (mm)	Surplus Rate (%)	Surplus Volume (Mm3)
L82B	404.92	677.73	151.77	22.39%	61.45
L82C	362.33	685.75	162.50	23.70%	58.88
L82D	591.39	577.91	101.01	17.48%	59.74
L82E	365.49	584.48	150.37	25.73%	54.96
L82F	168.84	511.83	112.02	21.89%	18.91
L82G	265.75	472.12	64.35	13.63%	17.10
L82H	230.32	450.54	63.64	14.12%	14.66
L82J	161.73	491.00	68.06	13.86%	11.01
L90A	260.91	541.59	66.84	12.34%	17.44
L90B	83.89	596.68	108.19	18.13%	9.08
L90C	60.83	607.44	152.74	25.14%	9.29
M10A	258.50	533.15	30.27	5.68%	7.83
M10B	249.62	557.46	68.40	12.27%	17.07
M10C	216.09	564.56	59.88	10.61%	12.94
M10D	62.61	470.64	39.62	8.42%	2.48
M20A	302.59	659.51	66.90	10.14%	20.24
M20B	124.83	724.94	126.78	17.49%	15.83
M30A	65.94	451.23	12.93	2.87%	0.85
N40B	130.69	318.50	0.00	0.00%	0.00
N40E	40.72	363.65	4.44	1.22%	0.00

Note:

Outcrop Area: The TMG outcrop area in the quaternary catchment;

Quaternary MAP: MAP (Mean Annual Precipitation) of the quaternary catchment;

Outcrop_MAS: MAS (Mean Annual soil water Surplus) on the TMG outcrop of the quaternary catchment;

Surplus Rate: The ratio of MAS to MAP;

Surplus Volume: The mean annual volume of soil water surplus.

Appendix 2

Baseflow separation result for quaternary catchments of TMG outcrop areas

Quaternary Catchment	MAR4Q (10^6m^3)	MAP4Q (mm)	Area4Q (Km^2)	Outcrop Area (Km^2)	Area_Ratio (%)	MAB4Q (10^6m^3)	MAB_OC (10^6m^3)	MAB (mm)	MAB/MAR (%)	MAB/MAP (%)
E10A	61.27	898.59	133.71	133.06	99.51%	12.04	11.98	90.02	19.65%	10.02%
E10B	69.78	736.31	201.94	166.61	82.51%	13.61	11.23	67.4	19.50%	9.15%
E10C	49.93	586.91	192.46	191.81	99.66%	9.51	9.47	49.39	19.05%	8.42%
E10D	48.98	518.44	234.9	234.62	99.88%	9.27	9.26	39.48	18.93%	7.62%
E10E	52.38	419.03	365.78	362.4	99.08%	9.83	9.74	26.87	18.77%	6.41%
E10F	52.58	406.98	385.82	385.82	100.00%	9.84	9.84	25.51	18.71%	6.27%
E10G	69.13	407.45	508.42	508.42	100.00%	12.92	12.92	25.42	18.69%	6.24%
E10H	33.53	494.87	162.16	162.16	100.00%	6.53	6.53	40.29	19.48%	8.14%
E10J	30.02	343.98	468.44	468.44	100.00%	6.21	6.21	13.26	20.69%	3.85%
E10K	4.71	283.59	235.42	191.83	81.48%	0.45	0.37	1.92	9.55%	0.68%
E21A	34.9	620.03	189.92	15.59	8.21%	7.38	0.61	38.84	21.15%	6.26%
E21D	45.37	626.57	241.82	105.02	43.43%	9.57	4.16	39.58	21.09%	6.32%
E21E	19.59	360.34	292.74	73.44	25.09%	4.13	1.04	14.11	21.08%	3.92%
E21F	16.47	288.89	378.44	50.17	13.25%	3.46	0.46	9.15	21.01%	3.17%
E21G	30.6	475.12	266.02	111.81	42.03%	6.52	2.74	24.52	21.31%	5.16%
E21H	38.13	428.52	404.25	404.25	100.00%	8.09	8.09	20.02	21.22%	4.67%
E21J	18.78	337.97	316.59	233.06	73.62%	3.96	2.91	12.5	21.09%	3.70%
E21K	21.53	351.89	330.24	265.35	80.35%	4.64	3.73	14.05	21.55%	3.99%
E22C	13.36	323.92	489.29	1.01	0.21%	1.47	0	3	11.00%	0.93%
E24A	17.27	392.57	254.64	236.86	93.02%	2.04	1.9	8	11.81%	2.04%
E24B	10.29	272.43	467.54	3.41	0.73%	1.16	0.01	2.49	11.27%	0.91%
E24J	20.48	235.18	1077.61	357.2	33.14%	2.28	0.76	2.11	11.13%	0.90%
E24K	10.17	237.68	651.88	340.51	52.23%	1.16	0.61	1.78	11.41%	0.75%
E24L	23.21	310.58	515.82	459.04	88.99%	4.76	4.24	9.23	20.51%	2.97%
E24M	9.78	264.99	528.67	503.53	95.24%	1.05	1	1.99	10.74%	0.75%
E32E	2.6	192.6	1001.12	233.79	23.35%	0.28	0.07	0.28	10.77%	0.15%
E33A	0.95	135.94	1355.16	0.03	0.00%	0.1	0	0.07	10.53%	0.05%
E33B	0.28	113.9	702.12	6.45	0.92%	0.03	0	0.04	10.71%	0.04%
E33C	0.98	139.7	980.35	17.29	1.77%	0.1	0	0.11	10.20%	0.08%
E33F	3.33	212.3	724.88	156.03	21.53%	0.36	0.08	0.49	10.81%	0.23%
E33G	2.5	186.01	894.74	228.83	25.58%	0.28	0.07	0.31	11.20%	0.17%
E33H	0.57	133.77	719.04	197.08	27.41%	0.06	0.02	0.09	10.53%	0.07%
E40C	6.78	285.29	529.98	199.53	37.65%	0.79	0.3	1.49	11.65%	0.52%
E40D	7.02	284.26	543.98	494.43	90.89%	0.81	0.73	1.48	11.54%	0.52%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	**(10^6m^3)**	**(mm)**	**(Km^2)**	**(Km^2)**	**(%)**	**(10^6m^3)**	**(10^6m^3)**	**(mm)**	**(%)**	**(%)**
F60E	0.32	115.63	794.19	20.44	2.57%	0.03	0	0.03	9.38%	0.03%
G10A	174.27	1580.24	171.78	129.61	75.45%	42.45	32.03	247.13	24.36%	15.64%
G10B	91.48	1245.12	125.97	119.39	94.78%	21.79	20.65	172.94	23.82%	13.89%
G10C	146.84	1009.21	328.09	41.45	12.63%	9.51	1.2	28.97	6.48%	2.87%
G10D	115.51	625.39	687.61	9.11	1.33%	24.8	0.33	36.06	21.47%	5.77%
G10E	68.34	639.95	394.07	100.03	25.39%	14.57	3.7	36.96	21.32%	5.78%
G10F	60.84	514.65	539.39	19.66	3.65%	12.95	0.47	24.01	21.29%	4.67%
G10G	124.02	912.31	185.57	184.26	99.29%	25.04	24.87	134.95	20.19%	14.79%
G10H	21.18	411.34	674.62	28.6	4.24%	4.44	0.19	6.58	20.96%	1.60%
G10J	34.87	446.98	867.68	39.31	4.53%	7.18	0.33	8.28	20.59%	1.85%
G10K	25.16	381.85	1176.42	271.5	23.08%	3.14	0.72	2.67	12.48%	0.70%
G10M	17.44	300.29	2006.58	5.67	0.28%	2.11	0.01	1.05	12.10%	0.35%
G22A	31.61	683.68	238.14	236.69	99.39%	6.17	6.14	25.93	19.52%	3.79%
G22B	32.42	922.56	109.47	82.71	75.56%	5.83	4.41	53.29	17.98%	5.78%
G22C	23.31	605.43	254.36	9.9	3.89%	4.77	0.19	18.76	20.46%	3.10%
G22D	40.69	737.93	246.14	29.12	11.83%	7.75	0.92	31.5	19.05%	4.27%
G22F	57.03	1464.5	65.69	36.84	56.07%	14.92	8.37	227.1	26.16%	15.51%
G22H	25.14	669.23	227.35	4.51	1.98%	5.18	0.1	22.77	20.60%	3.40%
G22J	58.89	1002.14	128.21	14.72	11.48%	14.94	1.72	116.55	25.37%	11.63%
G22K	23.95	769.08	79.83	5.43	6.81%	6.04	0.41	75.66	25.22%	9.84%
G30A	4.8	259.7	761.81	331.33	43.49%	0.52	0.23	0.68	10.83%	0.26%
G30B	18.9	393.6	658.54	51.34	7.80%	4.03	0.31	6.11	21.32%	1.55%
G30C	11.31	409.52	351.3	327.93	93.35%	2.39	2.23	6.81	21.13%	1.66%
G30D	11.92	384.31	534.67	241.74	45.22%	1.42	0.64	2.65	11.91%	0.69%
G30E	1.9	248.55	352.19	331.32	94.07%	0.2	0.19	0.57	10.53%	0.23%
G30F	6.79	285.23	780.29	762.76	97.76%	0.76	0.74	0.97	11.19%	0.34%
G30G	3.49	252.96	647.52	603.79	93.25%	0.19	0.17	0.29	5.44%	0.11%
G30H	3.34	213.96	1077.93	1068.31	99.11%	0.35	0.35	0.32	10.48%	0.15%
G40A	38.44	1120.5	71.53	67.95	95.00%	10.2	9.69	142.59	26.53%	12.73%
G40B	49.37	936.61	122.44	121.61	99.32%	12.87	12.78	105.1	26.07%	11.22%
G40C	105.29	1367.07	144.58	142.6	98.63%	27.99	27.6	193.57	26.58%	14.16%
G40D	142.48	983.8	327.18	327	99.94%	37.21	37.19	113.74	26.12%	11.56%
G40E	37.45	721.78	277.55	151.02	54.41%	6.94	3.77	24.99	18.53%	3.46%
G40F	21.71	515.27	422.36	28.14	6.66%	4.53	0.3	10.72	20.87%	2.08%
G40G	29.96	723.85	220.45	142.28	64.54%	5.53	3.57	25.09	18.46%	3.47%
G40H	11.7	697.83	95.93	90.55	94.39%	2.19	2.07	22.8	18.72%	3.27%
G40J	14.56	613.42	168.46	115.38	68.50%	2.9	1.98	17.2	19.92%	2.80%
G40K	19.31	495.81	428.98	33.47	7.80%	4.06	0.32	9.46	21.03%	1.91%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	(10^6m^3)	(mm)	(Km^2)	(Km^2)	(%)	(10^6m^3)	(10^6m^3)	(mm)	(%)	(%)
G40L	21.49	569.04	384.99	202.28	52.54%	4.51	2.37	11.71	20.99%	2.06%
G40M	22.6	573.53	392.91	322.68	82.12%	4.72	3.87	12	20.88%	2.09%
G50B	15.3	531.07	339.12	203.99	60.15%	3.24	1.95	9.55	21.18%	1.80%
G50C	14.71	488.76	421.17	113.06	26.85%	3.17	0.85	7.51	21.55%	1.54%
G50D	15.51	431.43	572.09	108.21	18.92%	3.28	0.62	5.74	21.15%	1.33%
G50E	9.52	448.41	313.05	61.19	19.55%	2.01	0.39	6.41	21.11%	1.43%
G50F	7.9	453.14	290.22	62.02	21.37%	1.74	0.37	5.99	22.03%	1.32%
G50H	15.3	370.52	889.07	7.69	0.86%	3.3	0.03	3.71	21.57%	1.00%
G50K	4.2	440.63	162.66	63.84	39.25%	0.94	0.37	5.8	22.38%	1.32%
H10A	39.23	512.39	233.6	5.58	2.39%	7.87	0.19	33.69	20.06%	6.58%
H10B	46.74	707.75	162.42	112.73	69.41%	9.48	6.58	58.39	20.28%	8.25%
H10C	69.1	673.63	259.55	173.46	66.83%	14.03	9.38	54.07	20.30%	8.03%
H10D	50.38	1018.86	96.94	96.78	99.83%	10.43	10.41	107.56	20.70%	10.56%
H10E	90.2	1403.76	84.81	81.61	96.23%	21.23	20.43	250.35	23.54%	17.83%
H10F	86.56	783.69	247.85	125.48	50.62%	17.79	9.01	71.78	20.55%	9.16%
H10G	95.54	787.83	270.39	136.91	50.63%	19.64	9.94	72.63	20.56%	9.22%
H10H	79.21	885.81	187.44	79.63	42.48%	16.31	6.93	87.03	20.59%	9.82%
H10J	183.62	1594.86	213.76	175.77	82.23%	43.71	35.94	204.46	23.80%	12.82%
H10K	110.94	1224.84	193.52	188.81	97.57%	26.81	26.16	138.55	24.17%	11.31%
H10L	8.99	476.16	95.77	28	29.24%	1.24	0.36	12.91	13.79%	2.71%
H20A	4.72	357.14	140.4	24.2	17.24%	0.54	0.09	3.84	11.44%	1.08%
H20B	4.12	590.35	124.34	78.17	62.87%	0.81	0.51	6.55	19.66%	1.11%
H20C	3.58	642.96	80.54	58.87	73.09%	0.68	0.5	8.41	18.99%	1.31%
H20D	27.91	695.97	100.64	100.43	99.79%	6	5.98	59.58	21.50%	8.56%
H20E	40.29	906.39	95.17	94.49	99.28%	8.69	8.62	91.26	21.57%	10.07%
H20F	11.26	796.88	116.53	91.81	78.79%	1.91	1.5	16.38	16.96%	2.06%
H20G	4.71	680.13	85.05	55.86	65.68%	0.87	0.57	10.22	18.47%	1.50%
H30A	16.32	442.57	284.03	66.52	23.42%	2.04	0.48	7.16	12.50%	1.62%
H30B	10.99	374.37	314.79	70.59	22.42%	1.24	0.28	3.94	11.28%	1.05%
H30C	23.32	479.55	326.94	188.28	57.59%	3	1.73	9.18	12.86%	1.91%
H30D	4.8	385.11	127.03	52.13	41.04%	0.55	0.23	4.34	11.46%	1.13%
H30E	8.89	440.89	153.66	20.37	13.25%	1.29	0.17	8.4	14.51%	1.91%
H40A	6.51	426.2	184.3	87.92	47.70%	0.77	0.37	4.16	11.83%	0.98%
H40B	3.7	577.49	240.42	141.05	58.66%	1.05	0.62	4.37	28.38%	0.76%
H40C	14.19	374.92	271.69	37.38	13.76%	1.8	0.25	6.63	12.68%	1.77%
H40D	24.77	556.67	181.7	83.2	45.79%	3.55	1.63	19.54	14.33%	3.51%
H40E	36.05	539.13	285.35	110.4	38.69%	5.1	1.97	17.88	14.15%	3.32%
H40F	9.11	292.83	339.79	3.09	0.91%	1.08	0.01	3.17	11.86%	1.08%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	(10^6m^3)	(mm)	(Km^2)	(Km^2)	(%)	(10^6m^3)	(10^6m^3)	(mm)	(%)	(%)
H40G	17.38	416.95	263.26	102.3	38.86%	2.58	1	9.8	14.84%	2.35%
H40H	18.19	460.8	207.81	29.47	14.18%	2.46	0.35	11.84	13.52%	2.57%
H40J	10.59	416.95	203.47	38.85	19.09%	1.51	0.29	7.45	14.26%	1.79%
H40K	12.47	405.74	270.42	185.45	68.58%	1.76	1.21	6.51	14.11%	1.60%
H40L	6.1	381.32	158.83	9.46	5.96%	0.84	0.05	5.31	13.77%	1.39%
H50A	6.88	335.28	264.35	55.94	21.16%	0.93	0.2	3.5	13.52%	1.04%
H50B	16.66	389.23	430.3	30.08	6.99%	2.27	0.16	5.26	13.63%	1.35%
H60A	87.67	1894.5	72.64	59.31	81.64%	19.91	16.26	274.1	22.71%	14.47%
H60B	118.4	1126.69	209.99	145.6	69.34%	26.39	18.3	125.69	22.29%	11.16%
H60C	83.76	891	216.86	131.57	60.67%	18.61	11.29	85.84	22.22%	9.63%
H60D	41.67	651.84	226.78	104.33	46.01%	8.69	4	38.33	20.85%	5.88%
H60E	29.68	639.74	170.42	71.25	41.81%	6.07	2.54	35.59	20.45%	5.56%
H60F	23.29	581.64	164.87	81.03	49.15%	4.74	2.33	28.75	20.35%	4.94%
H60H	19.71	464.01	252.86	60.66	23.99%	4.19	1.01	16.57	21.26%	3.57%
H60J	22.01	457.44	292.97	102.08	34.84%	4.69	1.63	16	21.31%	3.50%
H60K	11.62	371.23	262.04	55.38	21.13%	2.34	0.49	8.91	20.14%	2.40%
H60L	9.51	360.76	230.13	19.97	8.68%	1.91	0.17	8.31	20.08%	2.30%
H70A	13.18	414.4	223.62	8.08	3.62%	2.64	0.1	11.82	20.03%	2.85%
H70B	41.23	694.37	152.98	35.31	23.08%	13.51	3.12	88.32	32.77%	12.72%
H70C	14.03	372.52	287.18	66.67	23.21%	1.44	0.33	5	10.26%	1.34%
H70D	39.1	634.75	170.29	99.29	58.30%	12.72	7.42	74.68	32.53%	11.77%
H70E	47.55	741.05	156.72	76.94	49.09%	15.72	7.72	100.28	33.06%	13.53%
H70F	22.88	573.22	120.76	6.54	5.41%	7.42	0.4	61.43	32.43%	10.72%
H70H	7.4	395.42	399.76	38.89	9.73%	1.69	0.16	4.23	22.84%	1.07%
H70K	6.01	458.42	207.11	38.52	18.60%	1.34	0.25	6.49	22.30%	1.42%
H80A	31.11	596.95	148.92	148.92	100.00%	9.75	9.75	65.47	31.34%	10.97%
H80B	42.48	791.68	122.87	78.37	63.79%	13.66	8.72	111.22	32.16%	14.05%
H80C	8.2	479.37	284.61	27.26	9.58%	2.07	0.2	7.27	25.24%	1.52%
H90A	41.32	644.68	178.95	125.09	69.90%	13.3	9.3	74.32	32.19%	11.53%
H90B	28.74	663.76	118.09	116.68	98.81%	9.26	9.15	78.38	32.22%	11.81%
H90C	5.59	466.68	217.41	18.37	8.45%	1.42	0.12	6.51	25.40%	1.39%
J11H	2.41	239.58	650.9	132.19	20.31%	0.3	0.06	0.46	12.45%	0.19%
J11J	3.78	303.7	449.48	151.34	33.67%	0.46	0.15	1.02	12.17%	0.34%
J11K	1.6	220.61	515.49	47.46	9.20%	0.18	0.02	0.36	11.25%	0.16%
J12A	6.8	436.97	180.75	94.21	52.12%	0.85	0.44	4.7	12.50%	1.08%
J12B	2.41	268.18	250.85	36.59	14.58%	0.26	0.04	1.03	10.79%	0.38%
J12D	9.64	289.31	830.34	35.6	4.29%	1.09	0.05	1.31	11.31%	0.45%
J12F	4.47	245.27	709.39	121.42	17.12%	0.47	0.08	0.67	10.51%	0.27%

Quaternary Catchment	MAR4Q ($10^6 m^3$)	MAP4Q (mm)	Area4Q (Km^2)	Outcrop Area (Km^2)	Area_Ratio (%)	MAB4Q ($10^6 m^3$)	MAB_OC ($10^6 m^3$)	MAB (mm)	MAB/MAR (%)	MAB/MAP (%)
J12G	4.49	276.66	760.29	72.3	9.51%	0.57	0.05	0.74	12.69%	0.27%
J12H	4.29	259.53	548.95	196.14	35.73%	0.45	0.16	0.83	10.49%	0.32%
J12J	2.91	250.03	548.51	75.52	13.77%	0.31	0.04	0.57	10.65%	0.23%
J12K	1.6	192.47	516.22	44.2	8.56%	0.16	0.01	0.31	10.00%	0.16%
J12L	7.12	314.06	757.02	110.59	14.61%	0.86	0.13	1.14	12.08%	0.36%
J12M	3.48	289.94	482.63	100.7	20.87%	0.42	0.09	0.88	12.07%	0.30%
J13A	3.88	295.24	517.59	96.29	18.60%	0.49	0.09	0.94	12.63%	0.32%
J13B	3.42	305.67	401.51	96.71	24.08%	0.42	0.1	1.06	12.28%	0.35%
J13C	5.7	350.51	434.76	78.96	18.17%	0.71	0.13	1.63	12.46%	0.47%
J23E	7.41	328.97	224.99	77.77	34.56%	1.3	0.45	5.77	17.54%	1.75%
J23F	4.39	194.23	477.3	66.1	13.85%	0.5	0.07	1.05	11.39%	0.54%
J23H	2.59	199.38	264.01	59.58	22.57%	0.3	0.07	1.12	11.58%	0.56%
J23J	6.58	307.7	228.48	128.66	56.31%	1.19	0.67	5.2	18.09%	1.69%
J24F	0.79	221.7	282.15	21.44	7.60%	0.09	0.01	0.34	11.39%	0.15%
J25A	8.7	288.59	353.4	266.73	75.48%	1.59	1.2	4.5	18.28%	1.56%
J25B	13.61	325.57	396.56	265.59	66.98%	2.5	1.68	6.31	18.37%	1.94%
J25C	1.1	288.13	180.43	159.62	88.47%	0.14	0.12	0.76	12.73%	0.26%
J25D	9.61	365.23	210.24	53.85	25.61%	1.76	0.45	8.38	18.31%	2.29%
J25E	1	244.46	286.34	159.51	55.71%	0.13	0.07	0.44	13.00%	0.18%
J31A	9.61	441.05	447.04	311.14	69.60%	2.2	1.53	4.93	22.89%	1.12%
J31B	2.31	359.19	200.56	112.65	56.17%	0.57	0.32	2.83	24.68%	0.79%
J31C	2	369.2	167.97	103.3	61.50%	0.47	0.29	2.81	23.50%	0.76%
J31D	2	299.98	303.65	31.07	10.24%	0.51	0.05	1.67	25.50%	0.56%
J32E	5.15	234.34	971.15	63.8	6.57%	0.5	0.03	0.51	9.71%	0.22%
J33A	5.12	392.53	449.46	173.77	38.66%	1.22	0.47	2.71	23.83%	0.69%
J33B	9.22	436.91	590.72	220.15	37.27%	2.14	0.8	3.63	23.21%	0.83%
J33C	2.61	292.9	427.93	98.83	23.10%	0.29	0.07	0.68	11.11%	0.23%
J33D	12.4	378.95	258.86	93.3	36.04%	2.24	0.81	8.66	18.06%	2.29%
J33E	24.59	445.73	328.67	115.94	35.27%	4.75	1.68	14.45	19.32%	3.24%
J33F	11.7	343.28	365.62	47.69	13.05%	2.54	0.33	6.94	21.71%	2.02%
J34A	5.6	476.51	252.19	220.05	87.25%	1.27	1.1	5.02	22.68%	1.05%
J34B	12.88	569.32	341.55	211.37	61.89%	2.72	1.68	7.95	21.12%	1.40%
J34C	21.3	673.55	318.9	243.29	76.29%	4.21	3.21	13.2	19.77%	1.96%
J34D	7.72	470.83	354.2	179.09	50.57%	1.82	0.92	5.13	23.58%	1.09%
J34E	4.31	426.68	257.98	120.72	46.79%	1.07	0.5	4.16	24.83%	0.97%
J34F	4.71	415.04	319.96	85.65	26.77%	1.15	0.31	3.61	24.42%	0.87%
J35A	22.66	418.28	427.35	96.55	22.59%	4.72	1.07	11.05	20.83%	2.64%
J35B	9.38	410.49	651.13	237.24	36.44%	2.34	0.85	3.59	24.95%	0.87%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	(10^6m^3)	(mm)	(Km^2)	(Km^2)	(%)	(10^6m^3)	(10^6m^3)	(mm)	(%)	(%)
J35C	2.81	373.04	264.48	181.8	68.74%	0.74	0.51	2.78	26.33%	0.75%
J35D	25.31	406.5	506.95	46.64	9.20%	5.31	0.49	10.48	20.98%	2.58%
J35E	4.31	269.88	215.16	29.52	13.72%	0.87	0.12	4.06	20.19%	1.50%
J35F	18.31	341.33	500.04	146.41	29.28%	3.63	1.06	7.27	19.83%	2.13%
J40A	31.89	417.88	453.31	237.58	52.41%	6.17	3.23	13.6	19.35%	3.25%
J40B	17.2	431.15	221.84	212.11	95.61%	3.47	3.32	15.65	20.17%	3.63%
J40C	39.14	521.32	435.99	211.16	48.43%	8.77	4.25	20.12	22.41%	3.86%
J40D	25.48	445.61	654.5	14.28	2.18%	5.55	0.12	8.47	21.78%	1.90%
K10C	11.2	492.7	158.94	115.86	72.90%	2.66	1.94	16.71	23.75%	3.39%
K10D	5.71	454.11	163.88	2.88	1.76%	1.34	0.02	8.16	23.47%	1.80%
K10E	31.39	679.3	132.5	88.59	66.86%	9.49	6.34	71.6	30.23%	10.54%
K10F	4.89	502.44	105.73	1.34	1.27%	1.12	0.01	10.59	22.90%	2.11%
K20A	40.32	721.97	168.4	62.73	37.25%	14.11	5.26	83.81	35.00%	11.61%
K30A	52.52	752.85	195.94	53.21	27.16%	18.51	5.03	94.47	35.24%	12.55%
K30B	41.59	787.16	138.59	39.84	28.75%	14.77	4.25	106.58	35.51%	13.54%
K30C	54.03	805.11	190.06	77.51	40.78%	18.99	7.74	99.91	35.15%	12.41%
K30D	37.87	724.31	177.82	87.23	49.05%	13.18	6.46	74.1	34.80%	10.23%
K40A	18.7	705.57	87.47	79.08	90.41%	7.19	6.5	82.16	38.45%	11.64%
K40B	26.7	845.63	111.56	70.91	63.56%	10.15	6.45	91	38.01%	10.76%
K40C	33.77	930.39	99.6	51.9	52.11%	13.23	6.89	132.79	39.18%	14.27%
K40D	32.95	756.73	129.82	16.64	12.81%	12.81	1.64	98.69	38.88%	13.04%
K40E	53.12	864.32	267.61	220.03	82.22%	17	13.98	63.52	32.00%	7.35%
K50A	53.89	849.64	235.46	235.46	100.00%	19.9	19.9	84.5	36.93%	9.95%
K50B	48.47	881.94	202.91	202.86	99.98%	17.89	17.88	88.15	36.91%	10.00%
K60A	13.93	663.86	161.46	161.46	100.00%	4.56	4.56	28.27	32.74%	4.26%
K60B	17.42	753.6	143.2	143.2	100.00%	7.16	7.16	49.97	41.10%	6.63%
K60C	20.07	744.43	160.85	160.85	100.00%	8.57	8.57	53.25	42.70%	7.15%
K60D	44.57	814.63	292.62	292.62	100.00%	18.73	18.73	63.99	42.02%	7.86%
K60E	10.12	774.54	100.2	98.53	98.33%	4.54	4.47	45.34	44.86%	5.85%
K60F	23.6	806.46	242.13	188.96	78.04%	10.46	8.16	43.19	44.32%	5.36%
K60G	19.06	860	166.64	125.19	75.12%	8.43	6.33	50.57	44.23%	5.88%
K70A	25.86	920.11	170.42	170.41	99.99%	10.43	10.43	61.18	40.33%	6.65%
K70B	40.56	997.24	106.5	106.5	100.00%	14.55	14.55	136.6	35.87%	13.70%
K80A	70.04	1029.5	146	146	100.00%	26.78	26.78	183.42	38.24%	17.82%
K80B	94.71	1031.08	208.44	208.44	100.00%	35.5	35.5	170.31	37.48%	16.52%
K80C	79.11	1016.84	189.01	189.01	100.00%	29.13	29.13	154.12	36.82%	15.16%
K80D	65.95	936.19	173.21	173.2	100.00%	23.76	23.76	137.2	36.03%	14.66%
K80E	54.17	894.73	266.25	245.38	92.16%	14.47	13.33	54.33	26.71%	6.07%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	**(10^6m^3)**	**(mm)**	**(Km^2)**	**(Km^2)**	**(%)**	**(10^6m^3)**	**(10^6m^3)**	**(mm)**	**(%)**	**(%)**
K80F	33.97	545.68	221.32	157.73	71.27%	9.3	6.63	42	27.38%	7.70%
K90A	30.34	716.15	213.81	213.81	100.00%	7.55	7.55	35.29	24.88%	4.93%
K90B	25.54	774.13	149.84	145.81	97.31%	6.39	6.22	42.63	25.02%	5.51%
K90C	13.59	596.31	267.46	255.45	95.51%	3.97	3.79	14.84	29.21%	2.49%
K90D	17.11	692.62	215.66	116.3	53.93%	4.83	2.61	22.41	28.23%	3.24%
K90E	12.03	676.22	176.77	54.77	30.98%	3.54	1.1	20.03	29.43%	2.96%
K90F	18.82	698.55	250.86	125.7	50.11%	5.46	2.74	21.76	29.01%	3.12%
K90G	17.13	653.85	287.16	152.97	53.27%	5.01	2.67	17.44	29.25%	2.67%
L30A	2.99	283.94	360.95	0.16	0.04%	0.31	0	0.85	10.37%	0.30%
L50A	4.38	294.71	466.79	41.29	8.85%	0.45	0.04	0.97	10.27%	0.33%
L70A	3.08	248.48	582.22	49.92	8.57%	0.31	0.03	0.53	10.06%	0.21%
L70B	1.32	236.33	441.24	0.05	0.01%	0.13	0	0.3	9.85%	0.13%
L70C	2.65	224.18	662.89	89.7	13.53%	0.27	0.04	0.41	10.19%	0.18%
L70D	2.68	252.52	536.8	33.37	6.21%	0.28	0.02	0.53	10.45%	0.21%
L70F	3.31	315.95	307.07	111.86	36.43%	0.35	0.13	1.14	10.57%	0.36%
L70G	14.51	503.87	470.68	445.24	94.59%	4.17	3.95	8.86	28.74%	1.76%
L81A	17.7	526.84	332.39	331.78	99.82%	3.7	3.69	11.12	20.90%	2.11%
L81B	8.41	427.84	261.41	261.41	100.00%	1.84	1.84	7.04	21.88%	1.65%
L81C	11.39	436.73	332.49	332.49	100.00%	2.54	2.54	7.64	22.30%	1.75%
L81D	8.18	393.02	308.12	308.12	100.00%	1.89	1.89	6.13	23.11%	1.56%
L82A	15.02	595.06	269.28	269.28	100.00%	3.67	3.67	13.62	24.43%	2.29%
L82B	31.49	677.73	404.92	404.92	100.00%	7.45	7.45	18.4	23.66%	2.71%
L82C	28.6	685.75	362.33	362.33	100.00%	6.89	6.89	19.03	24.09%	2.78%
L82D	31.31	577.91	591.39	591.39	100.00%	8.11	8.11	13.72	25.90%	2.37%
L82E	18.51	584.48	365.49	365.49	100.00%	4.83	4.83	13.22	26.09%	2.26%
L82F	5.68	511.83	168.84	168.84	100.00%	1.63	1.63	9.64	28.70%	1.88%
L82G	7.11	472.12	265.75	265.75	100.00%	2.08	2.08	7.83	29.25%	1.66%
L82H	5.29	450.54	230.32	230.32	100.00%	1.52	1.52	6.61	28.73%	1.47%
L82J	5	491	164.28	161.73	98.45%	1.45	1.42	8.8	29.00%	1.79%
L90A	19.91	541.59	517	260.92	50.46%	5.76	2.91	11.14	28.93%	2.06%
L90B	37.68	596.68	366.69	83.89	22.88%	7.85	1.8	21.42	20.83%	3.59%
L90C	34.28	607.44	319.73	60.83	19.03%	7.19	1.37	22.49	20.97%	3.70%
M10A	15.97	533.15	265.09	258.5	97.52%	2.66	2.6	10.04	16.66%	1.88%
M10B	26.48	557.46	393.96	249.62	63.37%	4.4	2.79	11.17	16.62%	2.00%
M10C	30.57	564.56	431.31	216.09	50.09%	5.11	2.56	11.84	16.72%	2.10%
M10D	5.61	470.64	307.55	62.61	20.36%	0.49	0.1	1.59	8.73%	0.34%
M20A	20.31	659.51	362.72	302.79	83.48%	2.1	1.75	5.78	10.34%	0.88%
M20B	41.39	724.94	308.39	124.83	40.48%	7.36	2.98	23.88	17.78%	3.29%

Quaternary	MAR4Q	MAP4Q	Area4Q	Outcrop Area	Area_Ratio	MAB4Q	MAB_OC	MAB	MAB/MAR	MAB/MAP
Catchment	**(10^6m^3)**	**(mm)**	**(Km^2)**	**(Km^2)**	**(%)**	**(10^6m^3)**	**(10^6m^3)**	**(mm)**	**(%)**	**(%)**
M30A	5.05	451.23	258.71	65.94	25.49%	0.47	0.12	1.81	9.31%	0.40%
N40B	8.23	318.5	1213.03	130.68	10.77%	0.66	0.07	0.55	8.02%	0.17%
N40E	3.98	363.65	511.82	40.72	7.96%	0.34	0.03	0.67	8.54%	0.18%

Note:

MAR4Q: MAR (Mean Annual Riverflow) of the quaternary catchment;

MAP4Q: MAP(Mean Annual Precipitation) of the quaternary catchment;

Area4Q: Area of the quaternary catchment;

Outcrop Area: The TMG outcrop area in the quaternary catchment;

Area_Ratio: The percentage of TMG outcrop area in the quaternary catchment;

MAB4Q: MAB (Mean Annual Baseflow) of the quaternary catchment;

MAB_OC: The MAB that can be attributed to TMG outcrop areas.

MAB (mm): The MAB in the unit of mm of the quaternary catchment;

MAB/MAR: The ratio of MAB to MAR, presented in percentage.

MAB/MAP: The ratio of MAB to MAP, presented in Percentage.