# AN ANALYSIS OF BASEFLOW RECESSION IN THE REPUBLIC OF SOUTH AFRICA

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## DECLARATION

I wish to certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement has been made.

Signed: ..............................................................................

Gregory O. Hughes

## ABSTRACT

Demands on the water resources of South Africa are ever increasing owing to population growth and increased development of urban, peri-urban and rural communities. Problems in terms of water quantity and quality are likely to be experienced during baseflow recessions. It is therefore imperative that water resources managers not only understand these baseflow periods of streamflow, but are able to model them with confidence. Research for this study thus included a comprehensive literature survey of the factors which affect baseflow as well as the approaches that previous studies have utilised to analyse and model baseflow recession.

The primary aims of this study were to establish a streamflow database, to construct master recession curves (MRCs) for each catchment under consideration, evaluate the assumption that South African rivers recede exponentially, to determine a representative set of catchment characteristics for use in the baseflow recession analysis, to attempt to explain the MRC trends using these catchment characteristics and to investigate the feasibility of establishing a rule based model for baseflow recession.

A streamflow database for South Africa was therefore established. This consisted initially of 202 catchments which were deemed to be recording natural streamflow. MRCs were established for 134 of these catchments. Those MRCs which were established indicate that the majority of South African rivers do not conform to an exponential model of recession. In order to account for the trends defined by the MRCs, catchment area, average catchment slope, drainage density, mean annual precipitation, rainfall concentration, rainfall seasonality, two independent estimates of groundwater recharge and a geological index were calculated for each catchment. Limited success was achieved when the data set was divided into subsets in order to group catchments with similar baseflow recession responses. The geological composition of the catchments appeared to provide the best results in that those trends exhibited by the MRCs could be explained by the types and proportions of the lithologies present. Owing to the lack of readily useable results it was concluded that until further results were forthcoming the development of a rule based model for baseflow recession analysis in South Africa would be premature. The establishment of a readily accessible database containing streamflows and associated catchment characteristics lends itself to future research.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AMC | = | Antecedent Moisture Conditions |
| BFI | = | Base Flow Index |
| CCWR | = | Computing Centre for Water Research |
| CD | = | Compact Disk |
| CSIR | = | Council for Scientific and Industrial Research |
| DAE | = | Department of Agricultural Engineering, University of Natal, Pietermaritzburg |
| DEM | = | Digital Elevation Model |
| DWAF | = | Department of Water Affairs and Forestry |
| ET | = | Evapotranspiration |
| GIS | = | Geographical Information System |
| HOST | = | Hydrology Of Soil Types |
| LHGS | = | List of Hydrological Gauging Stations |
| KNP | = | Kruger National Park |
| MAP | = | Mean Annual Precipitation (mm) |
| MRC | = | Master Recession Curve |
| NDEM | = | National Digital Elevation Model |
| NES | = | National Exchange Standard |
| PCI | = | Precipitation Concentration Index |
| RDP | = | Reconstruction and Development Programme of the Government of South Africa |
| UNP | = | University of Natal, Pietermaritzburg |
| USA | = | United States of America |
| USGS | = | United States Geological Survey |
| WRC | = | Water Research Commission |

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# 1. INTRODUCTION

Adequate streamflow is required to satisfy agricultural, human and wildlife needs (Loganathan, Mattejat, Kuo and Diskin, 1986). It is realised, however, that that component of streamflow which will provide the limiting threshold to water requirements is baseflow (Browne, 1981). This limiting threshold should be viewed not only in terms of quantity but also in terms of streamflow quality. Hogg, Thompson and Striffler (1980) have expressed concern over recent non-point source pollution processes in wilderness catchments which they believe has developed a need for the accurate simulation of baseflows.

Despite these concerns, baseflow is probably the most neglected and least scientifically treated component of streamflow hydrology. It is usually treated as that portion of the hydrograph which is removed to obtain the direct runoff component of streamflow (Aron and Borelli, 1973). Anderson and Burt (1978) believe that the lack of adequate temporal data in the study of soil moisture within a hillslope is due to the preoccupation of researchers with stormflow rather than baseflow. The paucity of local literature suggests that baseflow research in South Africa has likewise been neglected.

The operation of modern integrated water supply systems are placing greater demands on water resources. The demand on already scarce water resources within South Africa is heightened by a rapidly expanding population along with the Reconstruction and Development Programme (RDP), which aims *inter alia* to provide improved water supplies to the informal peri-urban settlements which surround South Africas cities as well as to the many rural communities. These increases in demand have serious implications for South Africa where the proportion of the Mean Annual Precipitation (MAP) which enters the rivers is far less than 25%, with an average of approximately 10% (Alexander, 1985). South Africa is characterised by high incident solar radiation and high evapotranspiration (ET) losses. Hence the precipitation has to satisfy soil moisture deficits and as a result subsurface flows are reduced, contribute less to streamflow and play little or no role in providing short term flow stability (Alexander, 1985).

Consequently, there is not only a need to understand and model these baseflows, but also to improve methodologies for the analysis and modelling of baseflow within South Africa. The Department of Agricultural Engineering (DAE) at the University of Natal, Pietermaritzburg (UNP) undertakes water resources assessment and modelling with the *ACRU* model. The *ACRU* model has been under development since the early 1980's and is a physical conceptual and deterministic model which utilises daily multi-layer soil water budgeting techniques (Schulze, 1995a). In an attempt to react pro-actively to future modelling requirements, a baseflow research initiative was established.

The DAE undertakes field work in order to verify the *ACRU* model, to identify points of future research and to note the modelling requirements of other users. On occasion it has been noted that during baseflow dominant periods of streamflow, *ACRU* simulated values tend to be overestimating streamflow (Schulze, 1995b). In applying the *ACRU* model to instrumented catchments in Germany, Herpertz (1995) made such an observation. Owing to the fact that the current *ACRU* baseflow generation routines are based on limited studies undertaken by Schulze (1988) and Kienzle (1994), and acknowledging that the baseflow routines need to be placed on a sounder footing, further research, in the form of this dissertation, was undertaken.

Baseflow recession analysis and research has been shown to be useful in many different aspects of water resources planning and management, *inter alia,* in low flow forecasting for the management of water supply, irrigation, hydro-electric power supply and waste dilution; in mathematical modelling as calibration or input to rainfall-runoff models; in hydrograph analysis for the separation of the flow components; in frequency analyses for low flow statistics and in regional low flow studies for the indexing of a catchments storage capacity.

However, before any research results are discussed a clear understanding of what constitutes baseflow is necessary. This was facilitated by investigating the many views and definitions provided in the literature. These are summarised in Chapter 2.

Having defined what constitutes baseflow, it was necessary to determine which factors exerted an influence on baseflow generation and regulation. This was done by surveying the literature and summarising the relations established between various factors and baseflow. As such, baseflow occurs towards the end of the hydrological cycle and as a result will be affected by many factors. These factors include not only the physical characteristics of the catchment but those determining the supply, distribution and loss of water within the system. The dominant factors which affect baseflow are reviewed within Chapter 3.

Chapter 4 deals with the various baseflow recession analysis and modelling techniques that have been employed in the past. These are provided in the form of a literature review.

Chapters 2 through 4 not only introduce the various aspects of baseflow recession, but also serve to clarify definitions, assess methodologies and techniques, provide research direction and stimulate new ideas. Chapters 5 and 6, on the other hand, highlight the research objectives established for this study and the methodologies employed in order to achieve these objectives. The research objectives include descriptions of the data set utilised to undertake the research, those ideas adopted from the literature, along with the manner in which the many factors which affect baseflow were dealt with. Descriptions of the many computer programs written to assist in the analysis of the baseflow data set and the rationale on which these were based are provided as part of the methodologies.

The results which stem from the current research along with a discussion of their implications for the modelling of baseflow in South Africa are provided in Chapters 7 and 8. Owing to the nature of the results there are a number of recommendations for future research which are summarised in Chapter 9.

## 2. THE NATURE OF BASEFLOW

The actual route which a particle of water follows from the time it reaches the ground until it enters the stream is complex. Streamflow discharge is generally considered to consist of three components, namely, direct runoff, interflow and baseflow. The distinctions drawn between these flow components is, up to a point, arbitrary and, to a degree, artificial (Linsley *et al.*, 1958). Water may start out as surface runoff, infiltrate and complete the distance to the stream as interflow. However, the interflow may encounter an impermeable layer, exfiltrate and become surface runoff once again. Alternately the interflow may accrete to the groundwater store.

It is nevertheless convenient to visualise three main routes of travel, or sources, of runoff within a catchment. These sources may be depicted graphically as in Figure 1 where the structure of the hydrograph as well as the flow components are idealised.

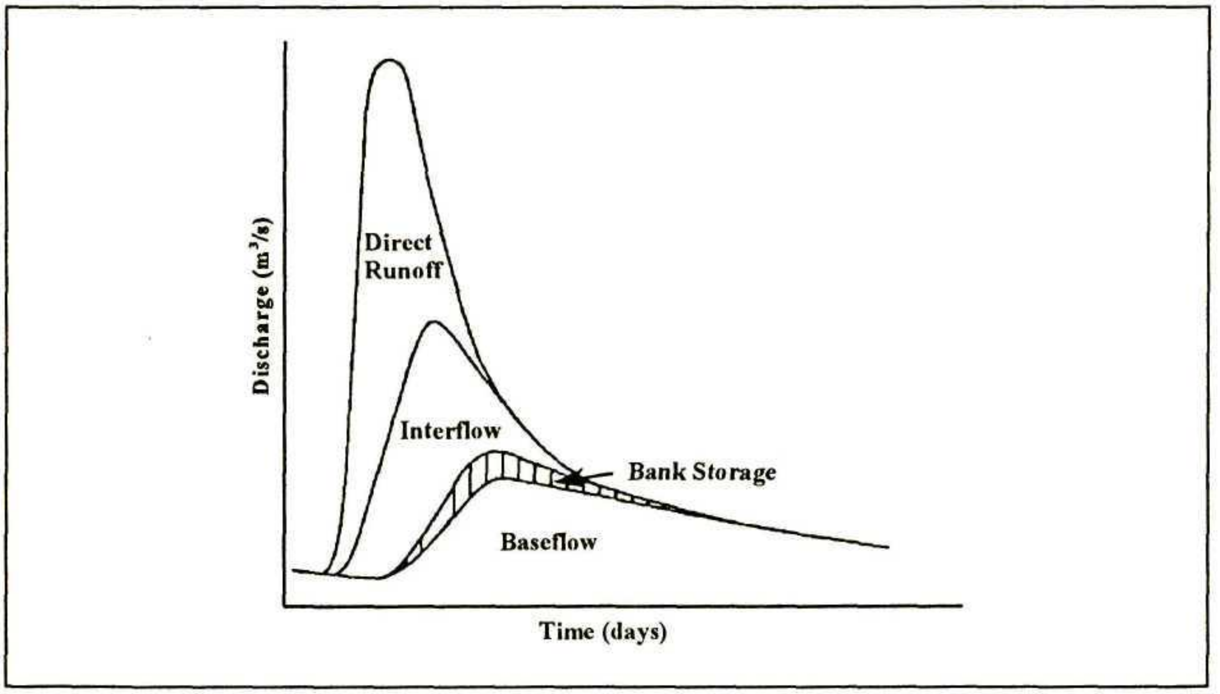


**Figure 1**: Idealised hydrograph with flow components (After Ineson and Downing, 1964)

According to Ineson and Downing (1964) surface, or direct, runoff is that part of precipitation which flows directly over the land surface into a stream or river channel, without having infiltrated the soil surface (Barnes, 1939; Linsley *et al.*, 1958). Interflow is considered to be that part of infiltrated water which moves relatively rapidly in approximately horizontal directions, usually through the soil (Barnes, 1939; Linsley *et al.*, 1958) or adjacent underlying zones, but does not accrete to the zone of saturation (Ineson and Downing, 1964). It is considered to arrive at the stream promptly, but later than the direct runoff.

Linsley *et al.* (1958) state that in limestone terrain the streamflow should be viewed as consisting of direct runoff and baseflow. They believe that the distinction is on the time of arrival at the stream rather than on the path followed and hence the direct runoff is considered to be composed of overland flow and a substantial portion of the interflow while the baseflow consists largely of groundwater. Riggs (1985) also states that direct runoff and interflow are often considered together.

However, hydrology, like many of the other sciences, has problems regarding the exact definitions of terms, their use by different researchers and the changes of these perceptions and use of the terms with time. This becomes evident if one examines the various names that hydrologists have applied to baseflow, which include: groundwater flow, groundwater discharge, low flow, dry-weather flow, percolation flow, under-run, seepage flow and sustained flow. Within the literature there appears to be no clear dividing line between where interflow ceases and where baseflow begins. Since baseflow is the primary focus of this research, a brief review of the various definitions of what constitutes baseflow is given.

One school of thought amongst researchers adheres rigidly to the premise that baseflow is derived solely from groundwater sources. Ideal baseflow is defined by Singh (1968, pg. 985) "as the flow to the stream from depletion of the unconfined aquifer when the factors such as evapotranspiration, leakage down to the underlying artesian aquifers or leakage upward from them, recharge from rain or irrigation water and pumpage or artificial recharge are not operative. In other words, this is the baseflow under idealised conditions from a given aquifer-stream system." Singh (1968) also provides a less ideal, but more general, definition of baseflow as being the net flow from groundwater storage to a stream. Similarly, Meyboom (1961) states that baseflow represents withdrawal of groundwater from aquifer storage after groundwater recharge has ceased. Possibly the most clear definition is provided by Linsley *et al.* (1958) and Ineson and Downing (1964), who believe that baseflow is derived from that portion of infiltrated water which reaches the zone of saturation below the water table. This water then percolates laterally through the saturated aquifer to be discharged into a river channel either as effluent, seepages or springs. The time lag for this type of seepage is greater than that which constitutes interflow and may be measured in days, weeks or months. Like direct runoff and interflow, baseflow is susceptible to fluctuations but these are less than the variations in other flow components.

A second school of thought is not as rigid in its views but is not necessarily any clearer about the issue. Vladimirov (1966) in providing a generalised definition of a low flow states that these occur when the river is fed mainly by subsurface waters but fails to define these sources fully. Curran (1990) also fails to shed any light on the sources of baseflow when he defines it as the component of the hydrograph derived from catchment storage. Yates and Snyder (1975) consider the recession to be derived from all natural storage, but fail to clarify these stores. Appleby (1970) states that hydrologists accept that a full range recession will include all post-peak flows which occur before the start of another event. This definition implies that other sources of flow like interflow, and even some direct runoff, would be included in such a definition. Similarly, baseflow is defined by Hall (1968, pg. 973) as "the portion of flow that comes from groundwater storage or other delayed sources". Some researchers have not been so vague as to the other sources of flow. For example, Saboe (1966, cited by Singh and Stall, 1971) defines baseflow as the groundwater component of total flow plus a component of interflow. Similarly, Hogg *et al.* (1980, pg. 756) defined baseflow as "the groundwater flow from a permanently saturated aquifer plus any subsurface lateral flow occurring as a result of soil drainage".

Kunkle (1962) believes that baseflow may be divided into two components, namely, catchment and bank storage discharge, the primary difference between the two being the origin of the groundwater. Catchment storage results from precipitation which has infiltrated the soil and recharged the groundwater. On the other hand during a flood stage of a stream the groundwater levels are temporarily raised near the channel by inflow into the stream bank. The volume of water stored and hence released at a later stage is referred to as the bank storage. Nathan and McMahon (1990) also note that bank storage may be considered as a fourth store or source which will contribute to the streamflow.

For the purposes of this dissertation, baseflow will be defined as that portion of flow which is derived predominantly from the groundwater store, although other delayed sources may also be present. This definition is in many ways a compromise between the various views held by researchers, as it accepts that it is easier to view and model individual and discrete stores of moisture. However, it also accepts that a small component of direct runoff, interflow or bank storage may be present and hence is believed to be a more complete representation of the complexities of nature and the interaction between the various sources or stores of moisture within a catchment.

## 3. FACTORS AFFECTING BASEFLOW : A LITERATURE REVIEW

Baseflow occurs at an advanced stage in the hydrological cycle and as such may be affected by a number of factors. The dominant factors include: climate, geology including surficial deposits, basin morphology, evapotranspiration (ET), bank storage and anthropogenic influences.

### 3.1 CLIMATE

A fundamental problem in groundwater hydrology is the determination of the groundwater runoff from a catchment for a given pattern of climatological elements (Dooge, 1960). Dooge is not alone in believing that climate is one of the major factors controlling baseflow characteristics, including occurrence and duration, as it determines the input into the system and a portion of the losses (Vladimirov, 1966; Ayers and Ding, 1967; Naney *et al.*, 1978; Arihood and Glatfelter, 1986; Kupczyk *et al.* 1994). In particular, precipitation is the driving force in terms of supply of water in the hydrological cycle. Hence the amount, distribution (spatial and temporal) and intensity of the rainfall received by a catchment along with the antecedent moisture conditions throughout the catchment will affect its baseflows (Laurenson, 1961; Freeze, 1972; Hayes, 1991). The temperature (Riggs, 1953; Vladimirov, 1966) or more directly the ET reflects a loss from the groundwater system (Hayes, 1991). This loss from the groundwater system due to ET is dealt with in more detail in Section 3.4.

Despite this importance which many researchers attach to climate with regards to baseflow, very few include a climate variable when attempting to establish a relationship between catchment parameters and baseflow using regression techniques. It would appear that climatic variables are either ignored, or the effects of climate are reduced by the selection of areas which are reasonably homogeneous in terms of climatic variables. When the effects of climate are investigated and climatic variables are included, the most common variable used is MAP (Hayes, 1991; Kobold and Brilly, 1994; Demuth and Hagemann, 1994). In order to account for climatic factors Pereira and Keller (1982a) divided the year into three time periods which were believed to represent different seasons in terms of rainfall frequency and evapotranspiration demand. Chang and Boyer (1977) developed a regression model which uses three catchment and two climatic parameters. The two climatic variables included in the model are the September mean 7 day 10 year maximum temperature and the September maximum number of consecutive rainless days. Inclusion of these two drought related parameters to the model increased the $R^2$ from 0.946 to 0.999 and reduced the standard error from 190% to 30%.

### 3.1.1 Climate Change

In noting the importance of climate on baseflow it is imperative that researchers consider the effects which climate change will have on baseflow. Wilkinson and Cooper (1993) provide such an insight. Using a simple idealised aquifer/river system, Wilkinson and Cooper (1993) studied the effects of climate change on such a system. They noted from Global Circulation Model studies of climate change that in the United Kingdom there was a likelihood of an increase in winter rainfall, which is when the dominant recharge of aquifers occurs. However, an anticipated increase in summer temperatures would be likely to shorten the period of recharge by increasing the soil moisture deficits that have to be met before groundwater recharge can take place.

Wilkinson and Cooper (1993) defined the response of an aquifer (Ta) in terms of its system parameters, namely, transmissivity, storage co-efficient and aquifer length. Aquifer systems with a low value of Ta were hypothesised to have a slow response to any recharge or abstraction perturbations while those with a high value would respond more quickly. The fact that aquifers have different response times to climate change as a result of aquifer properties is not unexpected. Wilkinson and Cooper (1993) noted four points related to water resource consequences:

(a) The response of the aquifer is governed by the Ta parameter such that aquifers with a high transmissivity, low storage and are of limited extent will have a rapid response to climate change.

(b) Any delay in the onset of recharge in the autumn may lead to enhanced low flows in rivers which are supported by rapid response aquifers, such as the chalk.

(c) For slow responding aquifers there may be an increase in baseflow with an increase in winter recharge, even if the length of this recharge period is reduced. However, for fast reacting aquifers there is likely to be a detrimental effect if the length of the recharge period is reduced, even if the volumes are increased by an increase in winter rainfall.

(d) Slow responding aquifers may take a considerable amount of time to reach a new storage equilibrium following a climate change, even if this change is gradual.

These observations once again highlight the importance of climate on baseflow generation and regulation. While these observations are localised in a global context they indicate the types of consequences that may result from a change in climate when considering baseflow.

### 3.1.2 Recharge

The timing and spatial extent of any recharge is likely to influence the groundwater dynamics and consequently the baseflow. Despite this obvious influence very little research has been conducted into this facet of baseflow.

Singh (1968) mathematically modelled the effects of precipitation on a set of idealised baseflow curves. He noted that the soils hydraulic and physical characteristics affect the time to the beginning of recharge and the magnitude and duration of the recharge. The recharge results in a shifting of the ideal baseflow curves either laterally in time or upwards in magnitude. Riggs (1953) was unable to attribute the difference between baseflow depletion rates for summer and winter to evapotranspiration alone. Riggs (1953) ascribes the rapid depletion of baseflow in the summer to the fact that the baseflow is coming from the high altitude areas of the basin where snow melt is occurring and infiltrating while the lower altitudes have had no substantial recharge. As a result the baseflow decreases more rapidly during periods in which the whole catchment receives uniform recharge.

The effects of climate, and indeed climate change, including their effects on recharge, are significant in any consideration of the mechanisms determining baseflow. These essentially provide the input and account for a portion of the losses from the physical system defined by the geology and soils.

## 3.2 GEOLOGY

The hydrograph which is measured at the outlet of a catchment contains information about the runoff processes occurring within the catchment. The recession limb of this hydrograph reflects the drainage of water from storage within the catchment. Analysis of the recessions should provide general information about the types of storage that feed the stream (Boughton and Freebairn, 1985), as well as information on the storage behaviour of aquifers within the catchment (Demuth and Schreiber, 1994; Tallaksen, 1995). Hence, the magnitude of baseflow provides important information on the permeability and storage capacity of the aquifers (Meyboom, 1961). Such an analysis of baseflow data thus provides a method of comparing characteristics of drainage basins and geological formations (Knisel, 1963).

Farvolden (1963, pg. 219) states that the fact "that geology is the major control on the hydrology of any area is generally accepted among geologists. The effect of such geologic factors as lithology and structure on such hydrologic factors as permeability, gain or loss in streams and occurrence of springs is confirmation of this belief." Browne (1981) similarly states that geology exerts a considerable influence on the level of baseflow. Farvolden (1963) and Browne (1981) are not alone in their views as several workers have pointed out the impacts of geology on baseflow estimation *eg*. Knisel (1963) for the south central United States of America, Schneider (1965) for Pennsylvania, Weyer and Karrenberg (1970, cited by Browne, 1981) for western Germany, Wright (1970) for southeast England, Grant (1971) for northern Ireland, Musiake, Inokuti and Takahasi (1975) for Japan and Pereira and Keller (1982b) for the pre-Alps. Freeze (1972) utilised a deterministic mathematical model to indicate the effects of the subsurface hydrogeologic configuration on streamflow. In fact, the influence of geologic factors on streamflow is perhaps most apparent during the baseflow periods during which the streamflow is being derived almost exclusively from groundwater sources.

In order to clarify the various geological terms which are used within this Chapter a simplified vertical section of the groundwater zone is illustrated in Figure 2. Relevant simplified definitions for geological terms are also provided (Maidment, 1992; Schulze, 1995a; Vegter, 1995).

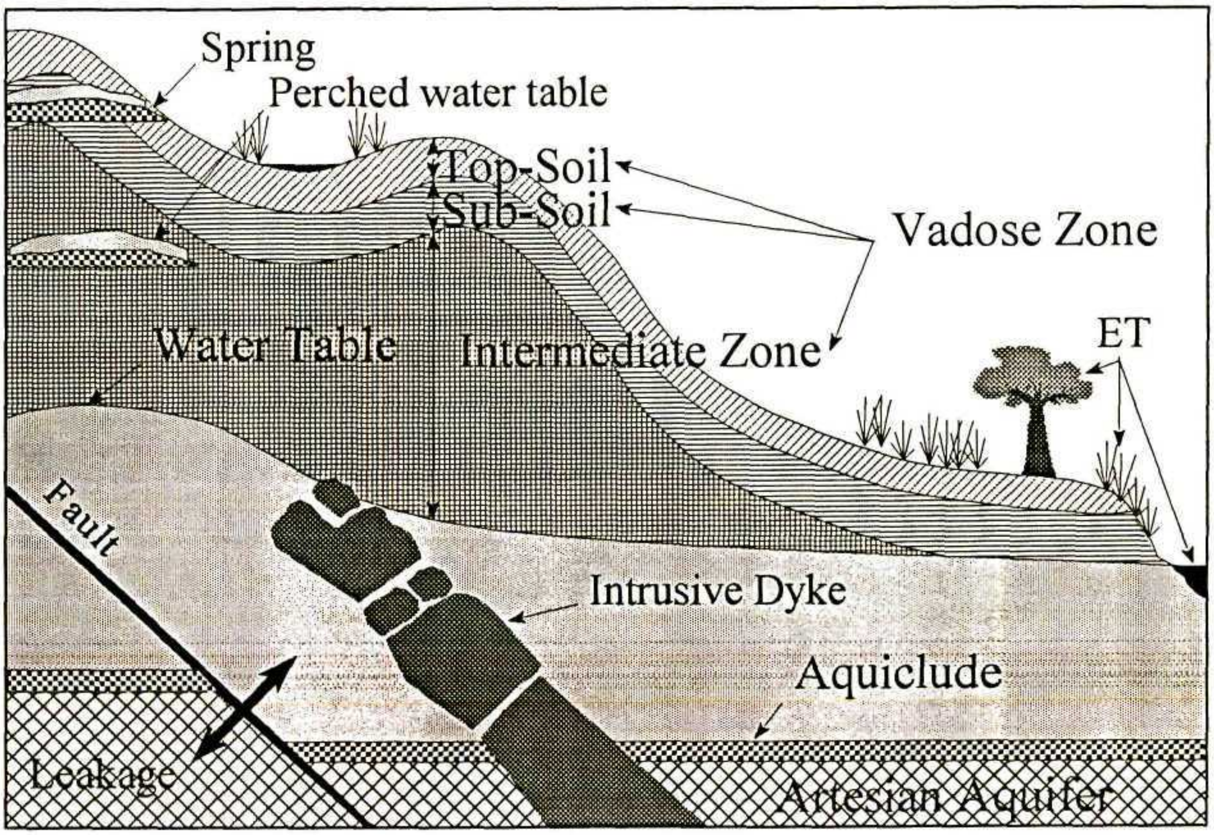


**Figure 2**: Idealised profile of the groundwater system

Sedimentary rocks: Clastic sedimentary rocks are formed from sediment derived from pre-existing rocks, *eg.* sandstone, shale, siltstone. Chemical sedimentary rocks are formed either by chemical precipitation or the accumulation of biochemical material, *eg.* limestone or dolomite.

Igneous rocks: These are rocks that have crystallised from a molten state. These may be intrusive if they solidified at depth, *eg.* granite, gabbro and dolerite, or they may be extrusive if they were formed from lava or volcanic ash, *eg.* basalt, andesite and tuff.

Metamorphic rocks: These are formed from both sedimentary and igneous rocks. These are recrystallised due to extreme heat or pressure. The magnitude of this temperature and pressure is referred to as the metamorphic grade and will determine the suite of minerals which crystallise.

Fracture: This is a breakage in the rock other than along a cleavage plane.

Fault: A fault is a fracture in rock along which there has been an observable amount of displacement.

| | |
|---|---|
| Fold: | This is a flexure in the rock. |
| Intermediate Zone: | This is the zone between the base of the sub-soil and the top of the capillary fringe. |
| Vadose Zone: | This is the zone below the ground surface but above the first principal aquifer. |
| Aquiclude: | This is a relatively impermeable layer. |
| Aquifer: | This is a permeable geological unit that can store and transmit significant amounts of water. |
| Water table: | This is the upper surface of the zone of saturation. It is the imaginary surface below which all of the pores and openings are filled with water. On this surface the pressure is equal to atmospheric pressure. |
| Lithology: | The description of rocks based on their colour, structures, mineralogical composition and grain size. |
| Lithostratigraphy: | Stratigraphy based on lithologic composition. |
| Stratigraphy: | The description of rock strata, be these sedimentary, metamorphic or igneous, in terms of lithologic composition, fossil content, age, origin and history. |
| Formation: | This is the fundamental unit in lithostratigraphic classification. The formation is generally characterised by some degree of lithologic uniformity or distinctive lithological features. |
| Group: | A Group is an assemblage of two or more successive Formations which exhibit similar lithologic features. |
| Supergroup: | A Supergroup is an assemblage of successive Groups and Formations which exhibit similar lithologic features. |

### 3.2.1 Geological Controls

Cross (1949) and Maxey (1964) classified the factors which act as geological controls on the hydrological processes of a basin. These are outlined below, along with examples to illustrate their effects, where appropriate.

(a) The permeability of the overburden which is the material overlying the zone of saturation will affect the amount of water which reaches the aquifer. This refers to the soil and where the water table is sufficiently deep it also includes the lithologies present within the intermediate zone (*cf.* Figure 2). The effects which the soils exert on baseflow are covered in more detail in Section 3.2.2.1.

Compact and crystalline rocks near to the surface reduce the groundwater recharge. This affects the regulating capacity of the catchment and results in lower baseflows. In permafrost regions the frozen ground serves the same role as compact, or impermeable, rocks (Vladimirov, 1966).

(b) The lithology of the zone of saturation will determine the composition, texture and sequence of the rock types, which in turn will influence the available storage space of the aquifer and of the zone of water table fluctuation. It will also influence the ability of the aquifer to transmit this water laterally towards the stream.

The storage capacity of the aquifer is dependent primarily on the porosity of the geology and surficial deposits (Knisel, 1963; Demuth and Schreiber, 1994). Primary porosity is the ratio of the pore volume to the volume of the sample and originates during the genesis of the rock type. This primary porosity is affected by subsequent physical and chemical processes, for example, compaction, cementation and recrystallisation. Catchments with a high storage capacity will usually display shallow recession curves. Aquifers that yield water from these primary pore spaces are referred to by Vegter (1995) as primary aquifers. Vegter (1995) notes that very few of South Africas aquifers qualify as primary aquifers.

The ability of the aquifer to transmit the water laterally towards the stream is dependent on the permeability of the lithologies. Similar to the porosity, permeability is also a function of genesis and affected by subsequent physical and chemical processes. In groundwater studies the term hydraulic conductivity is generally used and is a measure of the ability of a fluid to move through the pores within the rock. The hydraulic conductivity is thus a function of the medium and the fluid.

Schneider (1965) provides a good example of the lithological influence when he describes, in his study, that the lowest average flows are yielded in catchments which contain shales as these have a low permeability and storage capacity. However, sedimentary rocks are generally more likely to sustain low flows than igneous or crystalline metamorphic rocks as they are more permeable and have a higher porosity (Ayers and Ding, 1967). Vegter (1995) states that the primary porosity of igneous and metamorphic rocks may be disregarded as being of little or no consequence in South African groundwater hydrology. Typical values of porosity and hydraulic conductivity for different rock types are provided in Table 1. These observations hold for most lithologies, except where carbonates and highly fractured formations are involved.

**Table 1 :** Typical porosity and hydraulic conductivity values for general rock types (After Galfi and Kovács, 1981)

| Rock Types | | Porosity (%) | Rock Types | Hydraulic Conductivity (cm/s) |
|---|---|---|---|---|
| Igneous | granite | 0.3 | granite | $1.0 \times 10^{-4}$ to $0.5 \times 10^{-10}$ |
| | basalt | 0.8 - 17 | weathered granite | $1.8 \times 10^{-3}$ to $3.7 \times 10^{-4}$ |
| | tuff | 31 | basalt | $4.7 \times 10^{-5}$ to $2.1 \times 10^{-9}$ |
| | pumice | 87 | weathered basalt | $2.0 \times 10^{-1}$ to $1.7 \times 10^{-2}$ |
| Metamorphic | schist | 38 | schist | $3.3 \times 10^{-5}$ |
| | gneiss schist | 3 | weathered schist | $2.1 \times 10^{-4}$ |
| | shale | $2.5 \times 10^{-2}$ | shale | $6.0 \times 10^{-11}$ |
| | slate | 3.4 | quartzite | $2.0 \times 10^{-9}$ |
| | slate | 3.4 | slate | $1.3 \times 10^{-9}$ |
| Sedimentary | sandstone | 11 - 37 | sandstone | $4.0 \times 10^{-3}$ to $2.6 \times 10^{-7}$ |
| | conglomerate | 17 | conglomerate | $4.0 \times 10^{-7}$ |
| | siltstone | 9 | siltstone | $1.4 \times 10^{-7}$ |
| | dolomite | 2 - 9 | dolomite | $8.0 \times 10^{-5}$ |
| | limestone | 0.5 - 2.5 | limestone | $2.0 \times 10^{-4}$ |

Streams which are underlain by carbonates may exhibit highly variable baseflow. Vladimirov (1966) states that on the Silurian Plateau the karst terrain exhibits a high absorbtion capacity and yet it releases water slowly. However, the karst areas of the Crimean Yailas which also have a high absorbtion rate, have a low regulating effect in that they release water rapidly. Kupczyk *et al.* (1994) noted that the longest baseflows in Poland occur in catchments which have limestone as their bedrock. The carbonates may also be responsible for rapid depletion of streamflows which seep into these formations (Vladimirov, 1966).

(c) Structural geology refers to the faults, fractures and folds which disrupt the continuity and uniformity of the occurrence or sequencing of the rock types. It also introduces secondary porosity which results from the formation of fractures, faults and solution channels (Linsley *et al.*, 1958). This structure will affect the storage space of the aquifer by introducing secondary porosity thereby increasing the storage. Aquifers which provide water as a result of this secondary porosity are referred to by Vegter (1995) as secondary aquifers. Vegter (1995) notes that over approximately 90% of the area of South Africa groundwater occurs only within these secondary pores. The secondary porosity will also affect the ability of the aquifer to transmit water laterally to the stream. The introduction of faults and solution channels may increase the ability of the aquifer to transmit water laterally to the stream. Faults and folds may, however, also decrease this ability due to the disruption of the continuity and sequencing of the rock types.

Schneider (1965) noted that depletion of streamflow occurs where a stream passed over a Formation which is highly fractured and hence relatively permeable. In Norway, old crystalline rocks predominate and sizeable amounts of groundwater are only yielded in areas with extensive fracture networks (Tjomsland *et al.*, 1978). The basalt (finely crystalline igneous rock) of the Metolius River of the Columbia Basin is reported as having sufficient storage that baseflow would only decline from 50.97 $m^3/s$ to 21.24 $m^3/s$ in four years in the absence of recharge (McDonald and Langbein, 1948).

The presence of structures like faults and folds frequently provide weaknesses in the crust which intrusive igneous rocks are able to exploit when intruding. These intrusives typically include diabase and dolerite dykes and sills. Hydrologically these are considered to be impermeable, and frequently they disrupt the groundwater regime. These structures may also affect the boundaries which confine the aquifer. Singh (1968) used ideal baseflow curves to evaluate the effects of leakage from, or into, the aquifer. If the loss from the aquifer due to leakage is a dominant process then the recession will steepen progressively and the stream, after a time, may become influent. If the gain rate of leakage to the aquifer is a dominant process then the baseflow recession becomes flatter and the baseflow, after a time, will approach the gain rate. These are the effects for the extreme cases, but these effects have been shown to be present even when the gain or loss rate decays with time.

(d) The geometry of the aquifer will also exert an influence on the storage capacity of the aquifer. This is dependent on the relations between the dip of the rock strata and the gradient of the stream, as well as the relative positions of the aquiclude and the stream bed (Knisel, 1963). The position of the aquifer relative to the stream determines the areal extent of the groundwater basin which is not generally the same as the surface drainage basin. The aquifer's attitude (angle of dip) will affect its capacity and performance. For example, an aquifer which dips in an opposite direction to the slope of the stream would be capable of storing less water for baseflow than one which dipped in the same direction as the stream. An aquifer in a synclinal basin would also likely have a higher hydraulic gradient, and consequently a higher discharge rate, than an aquifer which is evenly extended over the basin (Knisel, 1963). The degree of stream entrenchment was found to cause a large variation in the baseflow by Singh (1968). For deep aquifers and shallow entrenched streams the baseflow will, in general decay, exponentially whereas for a fully penetrating stream the baseflow rate continuously decreases and plots as a curve on semi-log axes. Variation in the depth of entrenchment causes a large variation in the baseflow (Singh, 1968).

(e) Related to these geological factors is the anthropogenic influence of mining. The mining of various substances, notably coal, may have a distinct effect on the groundwater regime of an area. These effects are discussed, albeit briefly, in Section 3.6.

The various geological effects discussed above are generally inter-dependent and are difficult to isolate and evaluate without extensive field work and research (Knisel, 1963). It is apparent that the analysis of streamflow records may provide significant information concerning the groundwater geology of an area. However, much more would have to be known about the geological characteristics of an area before geological investigations would be able to replace streamflow measurements as a means of predicting streamflow. It was recognised nearly 50 years ago that complete answers to the problem would require close cooperation between geologists, hydrologists and engineers (Cross, 1949).

Pirt and Douglas (1982) and Hayes (1991) believe that in addition to the rock type, both soil type and soil depth are major influences on baseflow as they also determine the ability of a catchment to accept, store and transmit water. The influence of surficial geological materials on baseflow is therefore reviewed in the following Section.

### 3.2.2 Surficial Geological Materials

The role which surficial deposits, namely soils and alluvium, play in the generation and regulation of baseflow has been mentioned briefly thus far (*cf.* Section 3.2.1). However, it is deemed necessary to review these further.

#### 3.2.2.1 Soils

From the literature it would appear that the effects which geology has on baseflow have been researched to a far greater extent than those which soils exert. The infiltration capacity of the soil, along with its permeability, will affect the amount of precipitation which can reach the groundwater as recharge. For those hydrologists which accept that any baseflow recession is likely to contain a portion of interflow, the storage capacity of the soil is also likely to be of importance. That research which has been conducted appears to have concentrated on relating soils indices to baseflow indices. These soils indices typically take cognisance of the soil characteristics mentioned above.

Beran and Gustard (1977) derived a soil index, based on the ability of the soil to maintain baseflows. Two criteria were used for the derivation of this index: the infiltration rate, which will affect the recharge of the underlying geology and soil water storage, which will limit the amount of water which may be released at a later stage.

Similarly, Ayers and Ding (1967) noted that the steeper cumulative frequency curves, indicative of high streamflow variability, are associated with fine textured soils which exhibit poor internal drainage and reflect high rates of runoff during the rainy season and hence low rates of groundwater recharge. Catchments which contain medium to coarse textured soils are more likely to exhibit greater amounts of groundwater recharge and thereby are more likely to sustain baseflows. Ayers and Ding (1967) also noted a definite decrease in the recession constants as the textures become finer. When they computed the groundwater storage corresponding to the discharge value which is exceeded 90% of the time, this difference between the fine and coarse textured soils was magnified.

Gustard, Bullock and Dixon (1992) related the Base Flow Index (BFI), which is the proportion of baseflow to total flow, to the physical properties of the soil as determined in their Hydrology Of Soil Types (HOST) study. This HOST classification explains over 80% of the variability in the BFI. Curran (1990) related catchment recession coefficient to "land capability maps" using multiple regression techniques. These "land capability maps" were derived by a soil survey which defined thirteen categories established by considering climatic, slope, soil, wetness and erosion factors. The results achieved were promising with a correlation co-efficient of 0.925. In view of the fact that the soils map was difficult to obtain and that it resembles the geology map, Hayes (1991) excluded the soil type and depth variables from his regression analysis. Instead, Hayes (1991) retained the rock type as the variable describing the effects of the soil type and depth on baseflow.

The studies of Ayers and Ding (1967), Curran (1990) and Gustard *et al.* (1992) all suggest that there is a close link between soil properties and baseflow indices. However, Gustard and Irving (1994), in relating soil units to various indices of low flow, found that while promising results were obtained these were, on the whole, not satisfactory for extrapolation to ungauged catchments.

### 3.2.2.2 Alluvium

In regions where baseflow is an important component of streamflow, unconsolidated geological materials may be of major importance in the storage and transmission of water. These deposits include river sediment and various forms of glacially deposited sediments, be these moraines, eskers or outwash deposits. Cross (1949) found that these glacial deposits yielded high rates of groundwater outflow while areas which contained glacial till and unglaciated areas yielded lower rates.

Highly variable daily streamflow discharges may indicate that rapid runoff and little infiltration occurs within a catchment. Uniform flows, on the other hand, are generally produced in basins in which much of the precipitation infiltrates and accretes to the groundwater on its way to the stream.

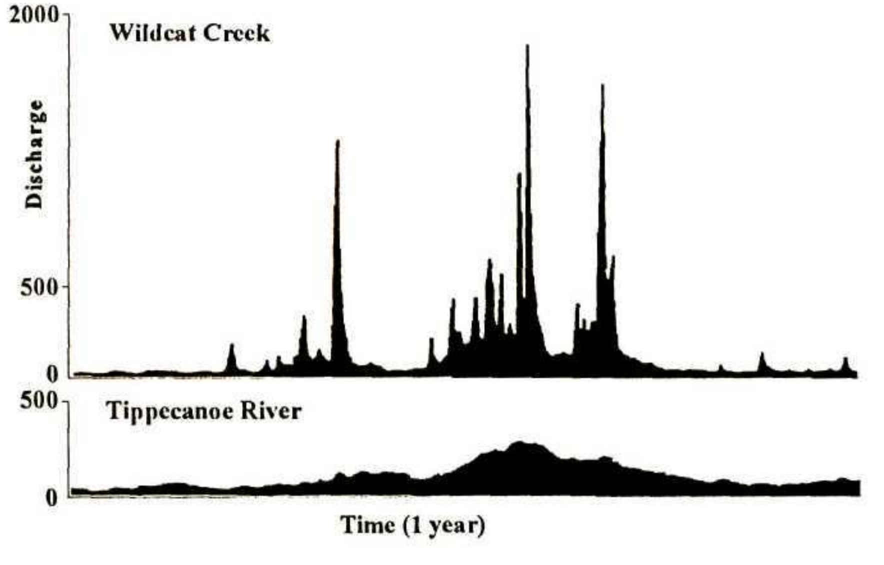


**Figure 3**: Contrast in the streamflow patterns of basins with different alluvial deposits (After Riggs, 1953)

Wildcat Creek referred to in Figure 3, is a basin which has a floor of clayey till, while the Tippecanoe River drains a catchment which has a great deal of sandy and gravelly glacial outwash deposits at the surface. These coarse glacial deposits infiltrate much of the precipitation thereby reducing the flood peaks but maintaining the baseflows (Riggs, 1953). Alluvium along the river banks may, however, restrict the flow of groundwater from the aquifers to the stream due to poor hydraulic conductivity and thereby reduce the baseflow. The alluvium may also limit the extent of aquifer recharge during river rises where bank infiltration and storage may be a dominant process. An example of this occurs in the Blacklands region of Texas where heavy clay soils predominate and bank storage is practically non-existent (Meyboom, 1961). Conversely, Kilpatrick (1964) found that the variability of the baseflow in the piedmont province of Georgia was primarily due to the regime of storage and discharge of the alluvial aquifer immediately adjacent to the stream channel.

Murakami (1989) studied the changes in the recession coefficient along the course of a river. He concluded that the recession coefficient in the upper most portion of the river represents the intrinsic recession coefficient for the predominant rock type near the gauging weir. Changes in this recession coefficient along the river course were attributed to the increase in thick gravelly and sandy deposits along the river course.

The effects, therefore, which surficial deposits and the underlying geology exert on baseflow, possibly render geological factors the most important of the factors which affect baseflow. However, of significant, if not equal, importance are the effects of basin morphology.

### 3.3 BASIN MORPHOLOGY

To date the practice amongst baseflow researchers when considering basin morphology has been to relate a number of morphological variables empirically to indices of low flow. Low flow indices are the parameters that are related to baseflows. These indices are typically derived from frequency curves, flow duration curves, low flow spells, series of annual minima and mean monthly or mean annual discharges. The relationship between the low flow indices and the morphological variables is usually established with the use of statistics, generally regression techniques (Beran and Gustard, 1977; Zecharius and Brutsaert, 1988a).

### 3.3.1 Establishing the Relationship with Baseflow

Regression equations relating catchment morphology to an index of low flow, may take on the form of, for example, Equation 1

$$Q_{d.t}=b_0 X_1^{b_1} X_2^{b_2} X_3^{b_3} \dots \tag{1}$$

where $Q_{d.t}$ is the d-day, t-year low flow statistic obtained from the flow record, the $X_i$ are measurable basin characteristics and the $b_i$ are parameter estimates obtained by multivariate regression procedures. These regional hydrological models are developed for estimating baseflows at the ungauged site by using readily available geomorphic and topographic parameters. Regional statistical models of this type are widely used in the United States of America (USA). Most of the studies developed to determine low flow statistics at the ungauged site have, however, met with limited success. In fact, Thomas and Benson (1970, cited by Vogel and Kroll, 1992) found that the average prediction errors for baseflow regression models were at least twice as large as those for flood flow regression models for the same basins.

These regional studies reveal two fundamental problems with this regression technique of analysis. Regression analysis ideally requires the parameters used to be independent and uncorrelated with each other. However, most geomorphological parameters are, to a v [illegible] ee, interrelated. This complicates the establishment of straightforward relationsh [illegible] nce many of the equations which have been derived by various studies have met w [illegible] uccess (Tjomsland *et al.*, 1978; Zecharius and Brutsaert, 1988a). In fact, Wright (19 [illegible] that baseflows may only be related to catchment characteristics provided that al [illegible], discharges, surface storages, underground leakages, groundwater catchment [illegible] flow regulations are known and may be accounted for and measured.

Secondly and more importantly is that many investigations [illegible] sent objective grounds for the selection of their catchment morphological characteristics as indices of the important hydrological processes within the relevant catchments. In other words, there is no evidence that these are the only variables that should be considered, or are the most important variables to be considered (Zecharius and Brutsaert, 1988a). Tjomsland *et al.* (1978) found that their various parameters were all intercorrelated and concluded that it was difficult to determine if the parameters themselves have physical meaning or were given a false significance because they were related to a more relevant physical characteristic.

Zecharius and Brutsaert (1988a) embarked on a two step procedure to identify the morphological parameters that should be analysed. First, they considered the smallest group of parameters that adequately describe the physical properties of a catchment. They surveyed the literature from previous studies and the parameters that had been identified in the past as being representative of overall basin morphology. They preferred parameters that were of hydraulic or hydrological significance. The procedure yielded 20 variables, which on the whole constitute a well balanced representation of the length, area, elevation, shape, form aspects and structure of their drainage networks. Secondly, they examined each parameter selected for a possible relationship with baseflow. The catchment characteristics which Beran and Gustard (1977) selected were limited to those that were readily available from maps. The selection of parameters was then based on:

(a) experience of previous hydrological studies,
(b) factors which are thought to affect baseflows and
(c) prevention of instability in the regression equations which occurs when intercorrelated variables are used.

### 3.3.2 Selected Morphological Parameters

Stemming from their research, Zecharius and Brutsaert (1988a) selected eight parameters which have a direct and known relationship with baseflow. Most of the parameters selected have been related empirically to baseflow in more than one previous study. The selected parameters are the following: drainage density, relative channel density, relief ratio, total relief, average ground surface slope, total length of perennial streams, average basin width and basin area. Zecharius and Brutsaert (1988a) used principal axis factor analysis to determine which of these variables contributed significantly to the variability in their data set. They determined three factors which accounted for 98.5% of the total variance, namely, a size , slope and dissection factor where each was characterised by the length of perennial streams, average ground surface slope and drainage density respectively.

Vogel and Kroll (1992) derived a physically based conceptual equation in an attempt to shed light on the baseflow process. This equation is as given in Equation 2

$$Q=2\alpha kAS^2K_b^t \qquad \textbf{(2)}$$

where $\alpha$ is the proportion of the catchment underlain by aquifer, k is the hydraulic conductivity in Darcys Law, A is the catchment area, S is the average slope of the actual land surface and $K_b'$ is the baseflow recession constant. Three of these independent variables, namely, the catchment area, average basin slope and the recession constant explained 97% and 93% of the variability associated with the seven day two year ($Q_{7,2}$) and the seven day ten year ($Q_{7,10}$) low flow statistics. Chang and Boyer (1977) found that the catchment perimeter, main channel length and the catchment form factor accounted for 95% of the variability of their $Q_{7,10}$. Hayes (1991) found that the basin characteristics which were significant in his regression analysis were drainage area, rock type and the strip mined area. Arihood and Glatfelter (1986) determined that the contributing drainage area and the flow duration ratio were the significant variables in their regression analysis while Kobold and Brilly (1994) identified catchment area, average annual rainfall, geology, main stream length and the slope of the main stream as significant variables in a study in Slovenia.

These are conclusions from but a selected few of the numerous studies that have been undertaken. However, having reviewed some of the results obtained it is apparent that large disparities still remain, as different researchers highlight different morphological parameters and few of the researchers have provided objective grounds for the selection of their morphological variables. These factors make it increasingly difficult to determine the relative effects of the various morphological parameters on baseflow. It also tends to suggest that highly localised catchment characteristics are likely to control the baseflow characteristics and makes it difficult to draw general conclusions which may be applied in other catchments. Added to this, is the fact that where researchers agree that a morphological parameter is linked to baseflow, they frequently provide different reasons for this link. Consequently, a more detailed analysis of the results obtained by the various researchers will serve little purpose. However, highlighting the proposed hydrological significance of the variables may be of benefit.

### 3.3.3 Hydrological Significance of the Morphological Variables

The hydrological significance of commonly utilised morphological variables proposed by various researchers are outlined below. These include catchment area, catchment slope and drainage density.

#### 3.3.3.1 Catchment area

The catchment area is commonly identified as a significant morphological parameter. Hayes (1991) believes that baseflows relate to drainage basin size better than to any other characteristic when a catchment is relatively homogeneous with respect to topography, geology and climate. Beran and Gustard (1977) and Hayes (1991) state that one would expect that an increase in catchment area would increase the magnitude of baseflows. Chang and Boyer (1977) believe that the catchment area is an effective parameter because it is related to the volume of input and storage. Ophori and Toth (1990) determined a baseflow-drainage area relationship and expressed this as a curve which displays a regular pattern. As the catchment size increases from initially low values, the specific baseflow rate increases quickly. Above a certain value of catchment size, in their case 6000 $km^2$, the rate of increase of the specific baseflow rate is reduced with further increase of the catchment area and approaches a limiting value. Ophori and Toth (1990) thus hypothesised that as one moves from catchments which contain high order streams to the larger scale catchments which contain low order streams one passes through basins which are increasing in size and are tending from relatively high to lower elevation ranges. Water which is recharged into a sub-catchment may not necessarily be discharged by that sub-catchment but may undergo an inter-subcatchment transfer. As a result an increasing amount of water is discharged with an increasing size of the catchment observed. Hence Ophori and Toth (1990) argue that the groundwater discharge becomes independent of catchment size above a certain value.

However, Arihood and Glatfelter (1986) prefer the use of the contributing area which they defined as the total drainage area less the area of internal drainages. They believe that the contributing area is most effective, because as the contributing area increases so does the streamflow. Arihood and Glatfelter (1986) found that the total drainage area introduced more error than the contributing area and consequently warn against the use of the total drainage area.

Browne (1981) found that it was not advisable to attempt to estimate flow at some ungaged point using the area-stream relationship. Zecharius and Brutsaert (1988a), upon considering their size factor reason that groundwater outflow will generally occur only over a portion of the catchment. Hence although the area and width of the catchment may have an effect on the baseflow only the length of perennial streams is a true reflection of where groundwater outflow is actually occurring.

Chang and Boyer (1977) note that the catchment perimeter is the factor correlated highest with low flow in their study. They were uncertain as to why it is higher than the catchment area which had been shown in previous studies to be the most effective parameter, although the two are highly correlated with each other. The catchment perimeter may be related to volume of input and storage or it may be expressing the form of the drainage system.

#### 3.3.3.2 Catchment slope

The catchment slope may influence the baseflow in a number of ways. The steeper the channel slope (slope of the catchment along the channel) the less overburden there is to store precipitation. In addition, the direct runoff would tend to be more rapid because there is less infiltration opportunity. In the course of streams flowing out of mountains and into valleys, for example, the stream slope decreases. If this decrease occurs quickly then it is possible that a stream experiencing baseflow conditions can disappear into the alluvial deposits associated with the stream (Hayes, 1991). Pereira and Keller (1982a) found that channel slope was related to the baseflow volume such that as the slope increased, the groundwater flow gradient increased and resulted in higher baseflow volumes. Average surface slope, which is the slope at right angles to the river, may also be significant to baseflow. For example, Zecharius and Brutsaert (1988a) state that aquifers in relatively steep catchments generally have faster depletion rates than those in catchments with relatively gentle slopes. Hayes (1991) believes that the slope of the catchment may affect the baseflows in that shallow slopes may facilitate more ET from the water table as it would tend to be closer to the ground surface.

#### 3.3.3.3 Drainage density

Zecharius and Brutsaert (1988a) state that many researchers have demonstrated a relationship between drainage density and baseflow. Tjomsland *et al.* (1978) believe that the drainage density is a measure of the catchments level of dissection and therefore is a measure of the travel times it takes runoff to reach the streams. As a result it is probably more relevant in smaller catchments. Similarly, Pereira and Keller (1982a) found that the baseflow recession coefficient increases with the drainage density which seems to be due to facilitated groundwater drainage. Drainage density tends to be inversely related to the permeability of an aquifer's material (Horton, 1932) and is a function of the same factors which control the infiltration capacity and transmissivity of soils and geological materials. It is therefore an indirect measure of these two properties (Zecharius and Brutsaert, 1988a). Browne (1981) believes that there are, however, problems with relationships derived between the drainage density and baseflow. These problems pertain to the measurement of drainage density due to differences in scale, the fact that the drainage density is a dynamic network and as to whether the network, as defined by contour crenulations, reflects current hydrological processes.

Despite the many opinions it is obvious that a catchments morphology plays a significant role in the derivation and regulation of baseflow. The varied nature of the relationships derived is probably a reflection of the complexities of nature and emphasises that different catchments have their own unique assemblage of characteristics. It also emphasises the fact that these morphological parameters cannot be viewed in isolation, as they are usually intercorrelated with each other and probably with many of the other dominant factors as well.

## 3.4 EVAPOTRANSPIRATION

It is clear that the shape of the recession curve is dependent on the geological and morphological characteristics of the basin but according to Webber (1961) is also dependent on the time of year. The time of year influences the baseflow due to temperature and vegetation influences, which affect the evapotranspiration losses. Nänni (1958), Kunkle (1962), Farvolden (1963), Chidley (1969) and Federer (1973) agree that some variation in the slope of the recession may be expected between seasons due to the effects of evapotranspiration.

According to Croft (1948) losses due to ET may be divided into those which occur from the slopes of the catchment and those which occur from the valley bottoms. The losses which occur from the slopes are largely those which are retained in the capillary spaces within the soil while those lost from the valley bottoms is due to riparian zone evapotranspiration from the zone of saturation. Reigner (1966) found that riparian zone evapotranspiration was separate from the catchment slope evapotranspiration by studying the levels of two wells situated away from the stream. The well levels were always well correlated with the stream discharge, but did not show the diurnal fluctuations which the streamflow hydrograph exhibited. He reasoned that if streamflow variations were also dependent on non-saturated zone evapotranspiration, then the well levels would surely exhibit the diurnal fluctuations.

Considerable interest has been shown on the subject of riparian zone evapotranspiration, which is defined as the transpiration by riparian vegetation as well as evaporation from the stream surface and adjacent riparian areas. Reigner (1966) believes it is difficult to separate the two. Evaporation from the groundwater increases as the water table approaches the ground surface, while the magnitude of transpiration is dependent not only on the season and temperature but also on the types of vegetation. Croft (1948) used a mean daily hydrograph to estimate monthly losses due to riparian areas. He suggests that water yield may be increased by preventing or minimising riparian water loss. In a short field study Rycroft (1955) showed the positive effects of the removal of riparian zone vegetation on increasing streamflow. Renard *et al.* (1964) noted that a reduction in the riparian vegetation known as mesquite, would substantially increase the amount of water available for use. The ratio of decline in the water surface during the growing season to the dormant season is five to one. Dambos are a seasonal wetland vegetation characteristic of central and southern Africa. They have been recognised as having significant hydrological significance particularly due to their occurrence in the headwaters of many rivers and due to their wetland like characteristics. Dambos are commonly believed to exert an influence on low flows. Bullock (1992) believes there is no evidence to suggest that dambos maintains low flows. In fact in areas where deeper soil units and a dominant baseflow regime occurs there is an influence on baseflow volumes but this is one rather of depletion of streamflow than augmentation. Reigner (1966) estimates riparian zone evapotranspiration losses to be as high as 23% of the streamflow.

### 3.4.1 Actual Versus Potential Streamflow

Rutledge and Daniel (1994), in developing a groundwater recharge estimation technique concluded that the amount by which the mean recharge exceeds the mean baseflow may be attributed predominantly to evapotranspiration from the riparian zone. This riparian water loss may in effect be viewed as the difference between the stream discharge measured at the gauging station and the groundwater runoff from the saturated riparian zones (Reigner, 1966). This introduces the concept of potential and actual streamflow. The concept of potential streamflow as explained by Tschinkel (1963) may best be described by a water balance equation for the riparian zone based on the cross-sectional diagram in Figure 4.

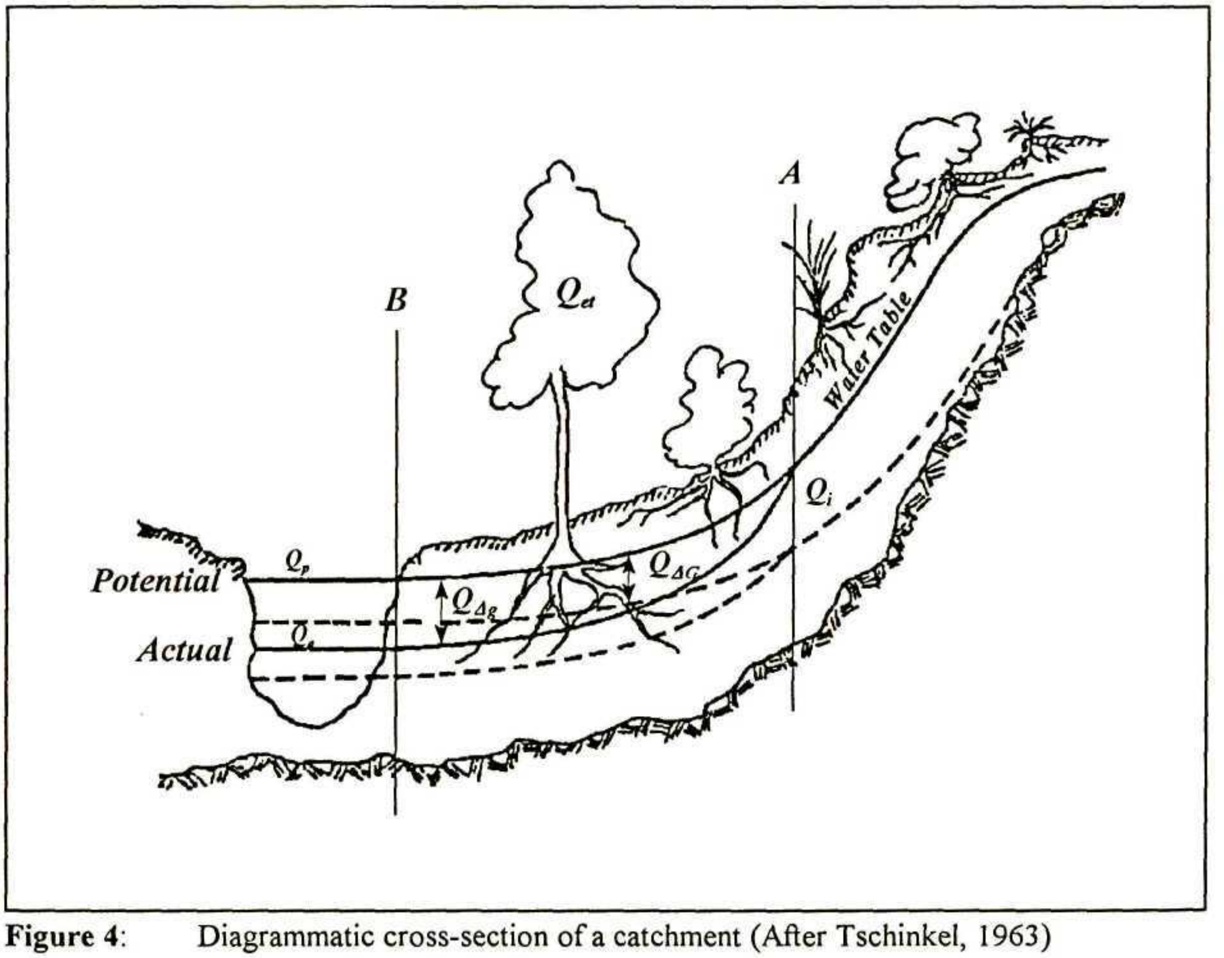


**Figure 4**: Diagrammatic cross-section of a catchment (After Tschinkel, 1963)

Let plane A be the upper limit of the riparian zone when it is at its maximum extent. Plane B is a similar plane but located near to the stream. The initial potential water level of the groundwater level is depicted by the upper solid line. Due to the groundwater depletion, the potential level of the groundwater table later in the season is depicted by the upper dashed line. Since this water table level decreases, there is a decrease in the storage of the riparian zone. The rate of change of the storage in this zone may be represented by $Q_{\Delta G}$. This change occurs in the absence of transpiration and may be reversed by groundwater recharge. The rate of inflow into the riparian zone across plane A is designated $Q_i$. The rate of outflow from the zone across plane B is designated $Q_p$. The water balance of the zone without transpiration is given by Equation 3.

$$Q_p = Q_i + Q_{\Delta G} \quad \textbf{(3)}$$

The actual outflow across the plane B is designated by $Q_a$ and the rate of evapotranspiration is represented by $Q_{et}$. The evapotranspiration may cause the water table level to drop to that labelled "actual" and this brings about a rate of change in the groundwater store of the riparian zone, $Q_{\Delta g}$. Thus, when evapotranspiration is significant the water balance in the riparian zone is given by Equation 4.

$$Q_a = (Q_i + Q_{\Delta G}) + Q_{et} + Q_{\Delta g} \quad \textbf{(4)}$$

Having established the concepts of actual and potential streamflow the fluctuations which occur in the baseflow may be considered.

### 3.4.2 Baseflow Fluctuations

The actual outflow is what is left after evapotranspiration losses have been removed from the inflows to the riparian zone. Since evapotranspiration varies, the actual outflow will also vary. When evapotranspiration ceases at night, the streamflow will not immediately rise to the potential discharge rate because of the losses which evapotranspiration has caused to the groundwater store of the riparian zone during the daylight hours. Part of the inflows at night have to be used to recharge the depleted water store (Tschinkel, 1963). If the drain on the store during the day is greater than that which can be recharged during the night then the deficit is carried over to the next day. Likewise if the evapotranspiration is low during the day then this gives the groundwater recharge mechanisms time to fill the deficit. The magnitude of the fluctuations decreases as the mean daily discharge decreases because the size of the riparian zone is diminished, the stream channel is shortened and the water table is lowered below the level of some of the plant roots (Tschinkel, 1963).

### 3.4.2.1 Daily fluctuations

Several workers have noted daily fluctuations in baseflow and have attributed the sharp daily decreases in flow to riparian water loss. Reigner (1966) noted that the points of minimum and maximum daily discharge did not correspond to the highest and lowest daily evapotranspiration losses. Instead they related to periods of equilibrium in which recharge of the saturated areas is equal to the stream discharge. The peak of the diurnal cycle is not necessarily at the groundwater runoff rate but is often quite considerably less. This is due to the fact that evapotranspiration never ceases completely or if it does, never long enough for the stream to recover to pure baseflow.

### 3.4.2.2 Seasonal fluctuations

In the same manner that the daily cycles of evapotranspiration affect the groundwater store and consequently the baseflow, so seasonal cycles of evapotranspiration will also affect the baseflow. Ando, Takahasi, Ito and Ito (1986) statistically analysed the seasonal variation of the fractional recession constant which indicated that the recession constants for spring, summer and autumn are 1.3, 1.5 and 1.2 times larger than those in winter. These results are considered to be dependent on the evapotranspiration rates in each season. The larger the evapotranspiration rate the larger the recession constant. As a result, the recession constants are larger for summer than for winter. The winter recession curve should represent the true groundwater discharge more closely as the losses to the atmosphere are lower. However, fluctuations above and below freezing may distort the winter baseflow recession (Riggs, 1985).

Harrold (1939), by studying the relationship between the levels recorded in a borehole and the stream discharge, noted that moderate to heavy rainfalls during the growing season had little effect on the water table levels. However, during the dormant season these moderate to heavy events were followed by a sharp rise in the water table levels and in the streamflow discharge. This indicates the seasonal influence on the groundwater store which is exerted by the evapotranspiration losses. Instead of using two seasons (dormant and growing) Chidley (1969) divided the year into four equal seasons as follows: January to March, April to June, July to September and October to December. Chidley (1969) used the values derived for these seasons as well as the values for the entire data set when developing his multiple regression equations to determine whether season had an effect on baseflow. He noted that the seasonal grouping did not significantly improve his correlations. Similarly, Riggs (1953) was unable to attribute the difference between summer and winter recession rates to evapotranspiration alone and concludes that this is due to the predominant influence of other factors. He ascribes the rapid depletion of baseflow in the summer to spatially non-uniform recharge.

## 3.5 BANK STORAGE

During and after a storm event within a catchment the groundwater level may rise and the apparent baseflow contribution to the streamflow increases. It is difficult to determine whether this apparent increase in the baseflow is due to recharge of the aquifer or whether it represents drainage from channel and bank storage, especially in ephemeral stream systems (Riggs, 1985).

Riggs (1985) describes how water table profiles in the near-stream zone indicate the direction of groundwater flow during a stage rise. During a period of baseflow the direction of flow is towards the stream. As the stage rises the water table gradient is decreased and may even be reversed. If reversed, then the stream becomes influent and water flows into the stream bank. At this time groundwater which would otherwise have been discharged into the stream is prevented from doing so and is stored further away from the channel. As the flood stage recedes the bank store drains and the water table gradient returns to its normal profile. These changes in profile are illustrated in Figure 5. It must be noted that during the stage rise the groundwater contribution to streamflow becomes negative and later increases above that of the previous baseflow as the stage decreases. The water stored in the near-channel area is referred to as bank storage and will take a short time to drain. Hence the recession will include bank storage, channel storage and groundwater discharge.

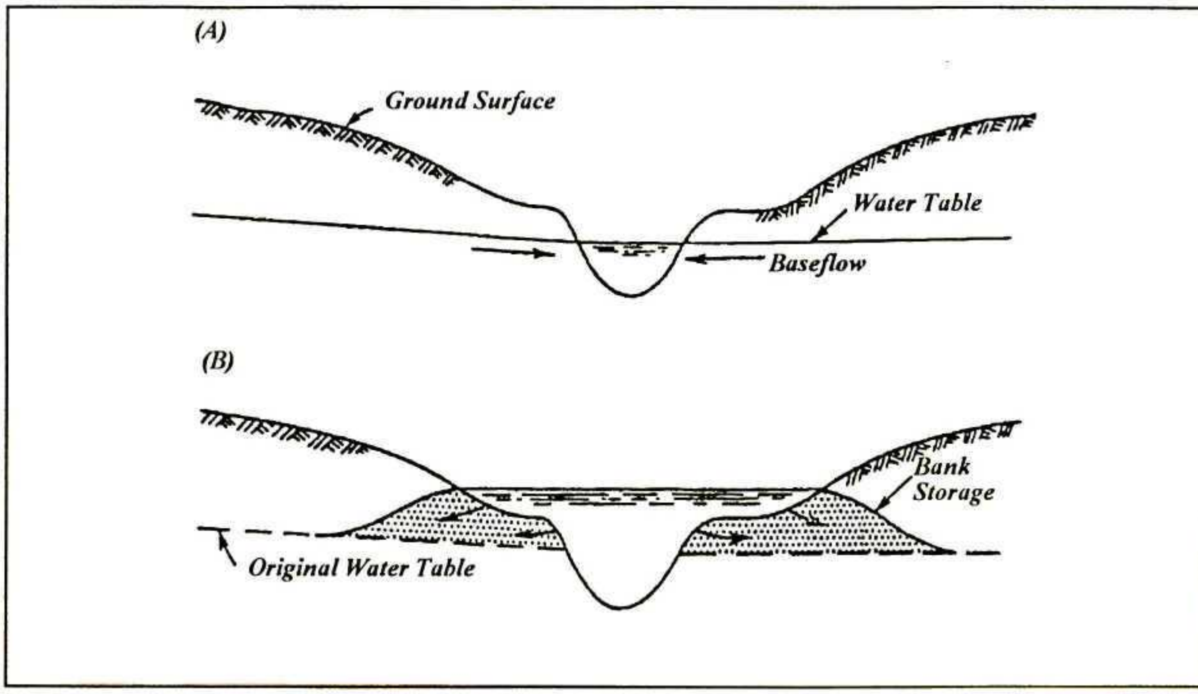


**Figure 5**: Bank storage variations during (A) baseflow conditions and (B) during a stage rise (After Linsley *et al.*, 1958)

Meyboom (1961) states that the variations in baseflow due to bank storage are due to the close hydrological link between the stream and the gravels along the stream bank along with their high permeability. The amount of water released from the bank storage during flood periods is uncertain but it has been shown by Todd (1955, cited in Meyboom, 1961) that the time required to re-establish groundwater discharge after a period of bank infiltration is relatively short.

Kunkle (1962) believes that the amount of bank storage at any one time can be considered to be less than that of catchment storage. Yet, the mean annual discharge from bank storage may equal or even exceed that of catchment storage because the rate of recharge and discharge from the bank storage is greater than that of the catchment storage. In essence the entire bank storage may be used several times during the year compared with the smaller use of the catchment storage. The slope of the recession line representing bank storage will be steeper than that representing catchment storage depletion. Meyboom (1961) in his study in the Calgary area found that the most important groundwater contribution to streamflow is bank storage.

## 3.6 ANTHROPOGENIC INFLUENCES

Human activities frequently affect the hydrological system, and consequently also baseflow. These effects are many and varied and it is not the intention of this study to provide a definitive review on these effects. Rather, the effects of land use change will be briefly highlighted along with a few other examples to serve as an illustration of these effects.

Land use changes may have a profound influence on the baseflows. Humans may modify the surface and groundwater hydrology to such an extent that the baseflow characteristics of a stream are altered significantly. This change may be gradual or it may be immediate and affects the runoff, infiltration and ET rates. These changes include the removal of forest areas for agricultural or urban development, the draining of wetlands and the construction of lakes or reservoirs.

Owing to the increase in impervious surfaces associated with urbanisation much of the precipitation that may have previously infiltrated may now become direct runoff. In certain instances where cities practise induced infiltration to decrease runoff to prevent the overloading of small streams there may be an increase in groundwater recharge (Hayes, 1991). Certain catchments reflect higher baseflows than adjacent ones due to the addition of sewage effluent from small towns or due to the importation of water from outside of the catchment. Groundwater withdrawal for domestic and industrial uses can have an influence on the discharge in nearby streams, particularly during baseflow periods (Fendekova and Nemethy, 1994).

The riparian zone vegetation is generally considered to be the most important when considering the effects of evapotranspiration on baseflows. However, as indicated by Talleksen and Erichsen (1994), other forms of vegetation on a basin scale, such as forests, may likewise have a marked effect. Compared with a grassland site catchments which are forested normally experience lower water table elevations (Kienzle and Schulze, 1992), soil moisture (Summerton, 1996) and runoff (Schulze and George, 1987) due to higher evapotranspiration losses. This evapotranspiration is composed of evaporation both from the soil and canopy/litter interception as well as from transpiration. A change in the vegetation within a catchment implies a change in interception losses and therefore a change in the net rainfall. As a result the catchments mean flow will be affected as will the baseflows. These reflect the changes in the soil water content and the groundwater levels (Tallaksen and Erichsen, 1994).

Owing to the effects which the urbanisation and forestry processes exert of baseflow many baseflow regression equations include a parameter to account for the degree of urbanisation or the percentage of forest present in the catchment *eg*. Arihood and Glatfelter (1986).

Reigner (1966) found that deviations from the ranges of baseflow indicated for various geological units was due to anthropogenic factors. In areas dominated by Pennsylvanian age lithologies, which consist predominantly of shales, sandstones and coal beds, lower baseflows are expected in areas unaffected by mining, whereas higher baseflows are expected in areas which have been mined and where the abandoned coal mines intercept more groundwater and increase their contribution to the streamflows. Current coal mining influences the headwater streams where pumping involved in mine drainage may decrease baseflows by as much as a factor of three.

The effects which humans have on the hydrological cycle are varied and have the potential to substantially alter the baseflow regime. The examples provided above serve to illustrate the types of effects that these departures from flows under natural conditions may have on baseflow. These anthropogenic effects have to a lesser or greater degree been ignored by many researchers but this does not diminish the role which they play in baseflow generation and regulation.

# 4. BASEFLOW RECESSION ANALYSIS AND MODELLING : A LITERATURE REVIEW

Having discussed the factors which affect baseflow and consequently the shape of the recession curve, it is necessary to review the methods of baseflow analysis and modelling that have been proposed and utilised by other researchers. These methods are outlined in the following Sections.

## 4.1 ELEMENTS OF RECESSION ANALYSIS

It is necessary to obtain a quantitative expression of the recession curve for comparative studies. This quantification process raises the following points of issue (Talleksen, 1995):

(a) Which analytical expression is preferable for the data being analysed?
(b) Which method should be used to obtain a characteristic recession?
(c) Which technique should be used to optimise the recession parameters?
(d) How does one treat the high variability present in the recession behaviour?

Recession analyses assess the outflow function:

$$Q = Q(t) \tag{5}$$

where $Q$ is the rate of flow and $t$ is time (Talleksen, 1995). There is no set manner in which this relationship may be determined. Some researchers have studied recession from a theoretical approach while others have determined empirical relationships. Hence there are almost as many methods of analysis as there have been works on the subject.

## 4.2 MODELLING APPROACHES

Talleksen (1995) provides a succinct summary of the various modelling approaches that have been adopted in the past. It is not the intention of this present review to highlight the theoretical and empirical considerations inherent in the development of these various modelling approaches. Section 4.2 serves merely to illustrate the types of approaches that have been attempted, while ensuing Sections (*cf.* Section 4.3) deal with the practical considerations of applying these approaches.

### 4.2.1 Modelling Recession from Basic Flow Equations

Singh (1968; 1969) presented many of the theoretical equations for groundwater flow which were derived from the Boussinesq equation. Brutsaert and Nieber (1977) gave a wide presentation of the theoretical equations for aquifer drainage used during the past century, many of which stem from Boussinesq's work. The decay of the aquifer outflow rate may be modelled as a function of aquifer characteristics using these theoretical equations of groundwater flow (Talleksen, 1995). In order to apply these theoretical equations one has to make simplifying assumptions concerning the physical properties of the aquifer and hence these equations are generally restricted to aquifers which are homogeneous, isotropic and confined by specific boundary conditions. Relationships of this type have been presented by many researchers *eg.* Singh and Stall (1971), Daniel (1976), Petras (1986), Zecharius and Brutsaert (1988b), Vogel and Kroll (1992) and Troch *et al.* (1993). These studies indicate that these relationships may be significant at the catchment scale provided it is relatively homogeneous. Applications in a heterogeneous catchment and at a regional scale are, however, likely to be limited.

### 4.2.2 Modelling Recession as Reservoir Outflow

The baseflow given by an exponential equation is the same as that from a simple linear storage model with no inflow. A simple exponential model does not fully represent recession flow over a wide range of flows and, as such, recession flow should be represented by a non-linear model or by more than a single linear reservoir (Talleksen, 1995). The outflow from a lumped storage model may be represented by a general function:

$$Q = KS^{p} \tag{6}$$

where $S$ is the storage and $K$ and $p$ are constants. The linearity of this store may be determined by plotting the hydrograph on semi-log paper. A model is considered linear if the plot forms a straight line on semi-log paper. If $p$ is greater than unity then the plot will be concave downwards and will be concave upwards if less than unity (Talleksen, 1995).

### 4.2.3 Modelling Recession as an Autoregressive Process

The basic exponential equation (*cf.* Section 4.3.2) with $t$=1, together with the addition of an error term can be recast as a first order autoregressive process as

$$Q_{t+1}=KQ_t+e_{t+1} \quad \textbf{(7)}$$

where $e_t$ represents the independent, but normally distributed errors, which have a zero mean and a constant variance. This model was proposed and used by James and Thomson (1970) to model baseflow recessions.

### 4.2.4 Empirical Relationships

The applicability of the basic exponential equation has been demonstrated by many researchers and today it is the most commonly used equation in recession analysis. More complex equations are still sought to account for a more complete range of flows. This is commonly achieved by subtle variations of the original *eg.* Toebes and Strang (1964), Clausen (1992), Otnes (1953, cited by Talleksen, 1995) and Tjomsland *et al.* (1978). Many of these equations are, however, not derived from first principles and are purely empirical.

The double exponential equation suggested by Horton (1933, cited by Hall, 1968) is according to Toebes and Strang (1964) a purely empirical equation. A further example is the hyperbola developed by Otnes (1953, cited by Talleksen, 1995) for southern Norway which takes the form

$$Q_t = at^{-1} - Q_0 \quad \textbf{(8)}$$

where $Q_0$ is the discharge at time $t$=0, $Q_t$ is the discharge after time $t$ and $a$ is a constant.

## 4.3 METHODS OF ANALYSIS

Owing to the fact that the analysis of baseflow recession curves provides valuable information concerning the parameters which govern the flow of groundwater, it is important that the analysis of recession curves be placed on a sound basis (Nutbrown and Downing, 1976). It has been realised since the early 1900s that recession limbs may be fitted well by mathematical solutions *eg*. exponential, double exponential or hyperbolic decay functions. Consequently, several methods have been proposed for the selection and analysis of baseflow recession and these are presented in the ensuing Sections.

### 4.3.1 Criteria for Selection of Recession Curves

Baseflow recession curves are derived from segments of a stream's discharge record (Riggs, 1985). It has been found that selecting these recessions from a continuous flow record for analysis is very difficult (Talleksen, 1995). Rainfall records are usually checked to ensure that the selected recessions are unaffected by precipitation. The time unit for recession is frequently taken as 24 hours, although on small basins finer time scales may be necessary (Riggs, 1985).

Talleksen (1995) notes that the start of a recession, or the initial discharge, can take the form of a constant or a variable. A constant value restricts the range of flow to fall below this given discharge. The discharge value may be related to an index of catchment wetness and, as such, assume that initial conditions of catchment wetness have been achieved at a given discharge (Talleksen, 1995).

A variable starting value may be defined as the discharge at a set time after rainfall, or the peak discharge, and hence it will assume different values for each event. Following the end of the storm sufficient time has to elapse to allow the direct runoff to exit the catchment and hence the first portion of the recession is generally excluded (Riggs, 1985; Talleksen, 1995). This may take from a few days for a small catchment up to a few weeks for a larger catchment. The last portion of the recession is often also excluded so as to remove the effects of the following event. The number of observations to discard is generally based on a knowledge of the response time of the catchment. Variable starting levels have been utilised by various researchers *eg*. Barnes (1939) or Singh and Stall (1971). Vogel and Kroll (1991) defined the start of the recession period when a three day moving average of streamflow began to decrease and to end when the same moving average began to increase. Linsley *et al.* (1958) state that the point of inflection on the recession limb is taken to mark the time at which surface contributions to surface flow ceases. After this point, the recession curve is deemed to represent withdrawal from the groundwater store.

A recession is said to last as long as the streamflow does not rise and/or rainfall above a certain threshold does not occur (Riggs, 1985). The recession length can therefore also be considered a variable or a constant. A minimum length of between four and ten days is generally selected (Talleksen, 1995). Riggs (1985) states that each of the recession segments selected should be at least of ten days' duration as shorter lengths may not be representative of baseflow recession. James and Thomson (1970) state that only daily flow sequences which are longer than seven days in duration should be utilised. Ando *et al.* (1986) and Smakhtin and Hughes (1993) studied recessions of longer than ten days and Nathan and McMahon (1992) used a minimum recession period of 15 days. Tallaksen (1989, cited by Talleksen, 1995) suggested that recessions with a constant initial discharge and a constant length be selected in order to reduce the variability introduced by the limitations of the simple exponential equation.

Clausen (1992) selected recessions in such a manner that the recession is at least eight days in duration, the discharge decreases during that period as well as the two preceding days, and that the recharge, defined as precipitation minus ET, in the riparian zone is negative during the recession period as well as during the two days preceding the recession. Bako and Owoade (1988) suggest that unless 13 days of consecutive flows are used for each recession segment, it would be necessary to discard the first few days of flow in order to remove any residual direct runoff or interflow components. They state that due to antecedent moisture conditions (AMC) and geological conditions it is difficult to provide a universal rule for the determination of the number of days to discard. Nänni (1958) did not use discharge readings earlier than five days after a stream rise. Bako and Owoade (1988) conclude that a minimum of three days be discarded and that a minimum of four days be left to define the recession constant.

Regardless of the recession selection criteria adopted a number of years of streamflow record are generally required to extract an adequate number of recession limbs. Most studies appear to be aware of this and researchers have usually selected stations with record lengths in excess of ten years.

### 4.3.2 Exponential Equations

The basic differential equation governing the flow in an aquifer was presented by Boussinesq (1877, cited by Hall, 1968). The original equation was non-linear and difficult to solve exactly. As a result, some simplifying assumptions were made which resulted in a form of the diffusion equation which may be solved more readily. Baseflow recession equations of the exponential type are the most commonly used and may take on the following forms (Barnes, 1939; Laurenson, 1961; Kunkle, 1962; Knisel, 1963; Toebes and Strang, 1964; Hall, 1968; James and Thompson, 1970; Singh and Stall, 1971; Yates and Snyder, 1975; Anderson and Burt, 1980; Petras, 1986; Talleksen, 1995)

$$Q_t = Q_0 EXP(-\frac{t}{a}) \quad \textbf{(9)}$$

$$Q_t = Q_0 EXP(-\alpha t) \quad \textbf{(10)}$$

$$Q_t = Q_0 k^t \quad \textbf{(11)}$$

$$Q_t = Q_0 (10)^{-t/b} \quad \textbf{(12)}$$

where $Q_0$ is the flow at a certain time, commonly $t$=0, $Q_t$ is flow at $t$ time units later and $\alpha$, $a$, $K$ and $b$ are constants. The value $EXP(-\alpha)$ is often replaced by the parameter $K$, which represents the recession constant or depletion factor. The constants $a$ and $b$ represent storage delay factors and have the dimension of time. Werner and Sundquist (1951, cited by Toebes and Strang, 1964) showed that diminishing flow from a confined aquifer can be expressed by Equation 9. Werner and Sundquist (1951, cited by Nathan and McMahon, 1990) also showed that this equation is the linear solution of the one dimensional general differential equation governing transient flow in artesian aquifers (the diffusion equation). However, Rorabaugh (1964, cited in Riggs, 1985) showed that the classic exponential equation is incorrect shortly after a recharge event. If a recession conforms to this simple exponential recession a plot of discharge versus time on semi-log paper will result in a straight line of slope log K (Toebes and Strang, 1964). Acceptance of the single exponential recession can be attributed to the ease of use and construction of the semi-log plots.

It can be shown that if the discharges in Equation 9 are replaced by volumes the form of the equation does not change. The volume of the flow ($V$) between times $t$-$T$ and $t$

$$V = \int_{t-T}^{t} Q dt = \int_{t-T}^{t} Q_0 EXP(-\frac{t}{a}) dt = aQ_0[EXP(\frac{T}{a})-1]EXP(-\frac{t}{a}) \quad \textbf{(13)}$$

For a fixed time interval $T$, such as a day, the equation reduces to

$$V_t = V_0 \ EXP(-\frac{t}{a}) \quad \textbf{(14)}$$

where $V_0$ is the initial discharge volume and $V_t$ is the discharge volume after time $t$. It then follows that the recession constant $a$ can also be estimated from the above equation.

### 4.3.3 Double Exponential Equations

If the plotting of a recession curve on semi-log paper yields a curve which is non-linear the curve may be represented by a double exponential equation such as

$$Q_t = Q_0 \ EXP(-\alpha t^{b}) \quad \textbf{(15)}$$

where $EXP(-\alpha)$ is equal to the recession constant, $K$, and $b$ is a constant (Singh, 1989). This double exponential equation was first suggested by Horton (1933b, cited by Hall, 1968) and according to Toebes and Strang (1964) is purely empirical. Data following a double exponential equation will plot as a straight line for $t^b$ against discharge on semi-log paper. The parameters $\alpha$ and $b$ can be obtained either graphically or with the use of least squares optimisation (*cf.* Section 4.4.2).

### 4.3.4 Hyperbolic Equations

Boussinesq (1904, cited by Hall, 1968) developed a non-linear equation for the case where a stream is located on a horizontal impermeable boundary with an initial curvilinear water table and zero water level in the stream. The resulting equation is

$$Q_t = \frac{Q_0}{(1 + ct)^2} \tag{16}$$

where $c$ is a constant. Werner and Sundquist (1951, cited by Toebes and Strang, 1964) derived this equation theoretically for unconfined aquifers. The curve will plot as a straight line for $Q_t$ versus $(1 + ct)$ on log-log paper. This equation has been used in Europe in connection with spring discharge (Hall, 1968). The constant $c$ may best be estimated using the method of least squares.

The problem with many recession curves is that despite their non-linearity they are not adequately fitted by equations 15 and 16. Maillet (1905, cited in Hall, 1968) and Boussinesq (1904, cited by Hall, 1968) proposed that two sources of baseflow may represent these non-linear curves where one is constant and the other declining. The following two ice-melt equations are the result.

### 4.3.5 Ice-melt Hyperbolic Equations

Boussinesq (1904, cited by Hall, 1968) proposed Equation 17 to cope with non-linear baseflows. In this Equation

$$Q_t = \frac{(Q_0 - b)}{(1 + ct)^2} + b \tag{17}$$

This equation resembles the hyperbola but has the constant $b$ included. Similarly, for snow and ice-melt conditions the baseflow recession may be adequately represented by

$$Q_t = at^{-n} + b \tag{18}$$

where $a$, $b$ and $n$ are constants (Toebes *et al.*, 1969 cited by Singh, 1989). As time increases the discharge approaches the constant value of $b$ asymptotically. A plot on log-log paper of $(Q_t - b)$ versus $t$ will result in a straight line (Toebes and Strang, 1964). This type of equation may typify baseflow recessions in catchments which contain snow and ice. The constants $a$, $b$ and $n$ can be determined graphically or by using the method of least squares. If the value of $b$ is taken as zero then

$$Q_t = at^{-n} \tag{19}$$

This equation was first suggested by Horton (1933b, cited by Hall, 1968) and has been used by Tjomsland *et al.* (1978) to study the recession characteristics of small Norwegian rivers. However, Tjomsland *et al.* (1978) failed to establish a relationship between the recession constants, $a$ and $n$, and basin characteristics. They noted that this was due to the constants being highly interdependent and that for a particular catchment they may take on quite different values without particularly changing the position or the shape of the curve.

### 4.3.6 Ice-melt Exponential Equation

Maillet (1905, cited by Hall, 1968) proposed another equation to deal with non-linear baseflow curves. Several researchers (*eg*: Toebes *et al.*, 1969, cited by Singh, 1989; Clausen, 1992) have suggested the use of Equation 20 for catchments which contain permanent snow and ice

$$Q_t = a + (Q_0 - a)K^t \tag{20}$$

where $a$ and $K$ are constants. Similar to the ice melt hyperbola this equation asymptotically approaches a constant value for large values of $t$. This baseflow defined by a is due to the melting of permanent ice and snowfields. The parameters $a$ and $K$ can be determined by plotting the above equation on semi-log paper. For an appropriate value of $a$, a plot of ($Q_t$ - $a$) versus $t$ will produce a straight line.

### 4.3.7 Combinations of Equations

Boussinesq (1904, cited by Hall, 1968) showed that a recession fitted by his ice-melt hyperbola (*cf.* Equation 17) could be equally well fitted by

$$Q_t = Q_{0_1} EXP(-\alpha_1 t) + Q_{0_2} EXP(-\alpha_2 t) \tag{21}$$

The non-linear equations highlighted in Sections 4.3.3 to 4.3.6 indicate that a non-linear recession curve can be decomposed into combinations of linear and non-linear curves. The same non-linear curve may be obtained from different combinations of these curves. Equations 17 and 20 are examples of the principle of superposition of linear solutions. This is a useful principle due to the ease of use and manipulation of the exponentials. Several workers have shown the advantages of using linear solutions to approximate non-linear systems (Hall, 1968). Many more equations could be devised, for example by adding another exponent to the ice melt exponential, but these equations were not encountered in the literature reviewed.

### 4.3.8 Convolution Approach

Yates and Snyder (1975) developed a convolution approach for the prediction of streamflow recession. A single linear storage element is utilised to represent the recession. They suggest that the volumetric recession may be represented by Equation 14. This method of recession analysis involves replacing the $V_0$ with a function of time and substituting convolution for the simple multiplicative operation in the equation.

## 4.4 DETERMINATION OF RECESSION CONSTANTS

The various recession constants described in aforegoing Sections can be determined by a number of means. These are described below.

### 4.4.1 Graphical Method

The recession constants, *eg.* $\alpha$, can be determined from the Master Recession Curves (*cf.* Section 4.5). Values of discharges are selected and the parameters calculated according to the equations. One problem with the method is that the parameters are determined by the discharges selected. Hence it is considered good practice to determine a number of values for each parameter and then define an average value for each parameter.

For each of the equations in Sections 4.3.2 to 4.3.6 the type of graph required to obtain a straight line plot and what the slope of this line represents was discussed. By fitting a straight line to the plotted data the recession parameters can be determined. The difficulty in this technique lies in obtaining a representative straight line fit.

One may also plot $Q_{t-1}$ versus $Q_t$ on a simple graph. If, for example, Equation 11 is valid then this plot will result in a straight line which passes through the origin. The slope of the line will specify the recession constant.

### 4.4.2 Least Squares Method

James and Thompson (1970) determined recession constants for the simple exponential equation by using the method of least squares. Any one of the equations given in Section 4.3.2 may be used for this purpose. Equation 11 may be recast as the following, if the measurement error in the recorded flows is modelled

$$Q_t = KQ_{t-1} + e_t \tag{22}$$

where $Q_t$ is the recorded flow on a given day, $Q_{t-1}$ is the true flow on the previous day, $K$ is the recession constant and $e_t$ is a random disturbance error on the specified day. The $e_t$ are assumed independent and to have zero means and homogeneous variance. The recession constant, $K$, can be estimated by minimising

$$R = \sum_{t=2}^{n} (Q_t - KQ_{t-1})^2 \tag{23}$$

The least squares estimate of $K$ is obtained by setting the derivative of $R$ with respect to $K$ equal to zero and solving for the value of $K$. This yields the following

$$K = \frac{\sum_{t=1}^{n-1} Q_t Q_{t-1}}{\sum_{t=1}^{n-1} Q_t^2} \tag{24}$$

Equation 26 provides a convenient method for estimating $K$ although the data should, if possible, be free of errors and contain large flows. An average value of $K$ obtained from a series of recession sequences would be provide more representative results. James and Thomson (1970) also describe a method for determining two and three recession constants for the cases where interflow and direct runoff are present in the recession limb and need to be accounted for.

### 4.4.3 Method of Moments

The recession constants may also be estimated by the method of moments (Singh, 1989). To determine a single parameter one may use the first moment about the origin ($M_1$). Any of the equations outlined in Section 4.3.2 may be used. For example, Equation 9 may be used to illustrate the technique, namely

$$M_1(Q) = \int_0^x t Q_0 EXP(-\frac{t}{a})dt \ / \int_0^x Q_0 EXP(-\frac{t}{a})dt = a \qquad \textbf{(25)}$$

Hence the recession constant $a$ can be calculated for a given baseflow sequence as it is equal to the first moment of that sequence about its origin. However, it is desirable to have a sufficiently long and error free baseflow record if this technique is used.

### 4.4.4 Matching Curve Method

This method was advocated by Hall and Narasimhan (1973) and can be used for the fitting of non-linear baseflow equations. The first step involves the establishment of the matching curves. The non-linear equation of interest is plotted for varying values of the variables to give a set of type curves. The field data are then plotted on axes of the same scale and overlaid over the type curves. The curve which fits the data the closest is used to define the variables of the non-linear equation. The value of this method is its ease of application. However, it is difficult to obtain reproducible matches as not all possible types of curve can be included on a graph.

### 4.4.5 Ratio Method

The ratio method was advocated by Hall and Narasimhan (1973) and was developed to overcome the problems associated with the matching curve method. The same data is used but expressed in the form of ratios for specified time intervals. The non-linear equation is put into suitable form by taking three values of discharge $Q_1$, $Q_2$ and $Q_3$ such that $t_2=\alpha t_1$ and $t_3=\beta t_1$ ($\alpha<\beta$). The resulting equations are then put into ratio form *eg*.

$$\frac{Q_2}{Q_1} = \frac{(1+\frac{\alpha t_1}{t})^{\frac{n}{1-n}}}{(1+\frac{\beta t_1}{t})^{\frac{n}{1-n}}} \qquad (26)$$

The plotting points can be obtained in terms of $\alpha$, $\beta$ and $n$ in a manner similar to that used to prepare the type curves of the matching curve method. Hence all that is needed from the field data are the ratios of $Q_2/Q_1$ and $Q_3/Q_1$ for determining the values of $\alpha$ and $\beta$. The ratios are then used on the ratio curves to obtain the values of, for example $n$. Where the recessions are sufficiently long the process can be repeated to verify the results. This method is advantageous in that it is relatively easy to apply and is likely to avoid errors made due to personal judgement. However, not all of the ratio curves can be included on a graph.

## 4.5 DERIVATION OF A CHARACTERISTIC RECESSION

A recession seldom runs to completion as it is generally disrupted by rainfall, particularly in a humid region (Riggs, 1985; Talleksen, 1995). This results in a series of recession segments of varying duration. It is therefore necessary to combine a number of recessions in such a way as to provide an average characterisation of a catchment's baseflow response. This average curve is generally referred to as the master recession curve (MRC). The MRC represents the "most frequent depletion situation" of a catchments receding baseflow (Nathan and McMahon, 1990). A major problem is the variability in the recession behaviour exhibited by these individual segments.

Master recession curve analysis techniques attempt to overcome these problems by constructing an average recession curve. Several methods have been developed to construct a MRC. Graphical techniques have commonly been used with the matching strip and the correlation methods being the preferred methods (Nathan and McMahon, 1990; Talleksen, 1995). Hall (1968) suggests that the correlation method is the more useful of the two.

### 4.5.1 Method of Experimentation

This method involves the plotting of discharge values for a recession period on semi-log paper. The best fit line is then drawn through the data points and the resulting curve is taken as the master recession curve. This curve is useful for prediction purposes (Singh, 1989).

Klaasen and Pilgrim (1975) plotted their data on semi-log graph paper to determine a recession constant. This allowed for a visual inspection of the data, as well as indicating any irregularities that were present. Where Klaasen and Pilgrim (1975) noted any irregularities in the recession curves they either eliminated the recession if the irregularity was large, or corrected the irregularity by eye in the case of a minor irregularity.

### 4.5.2 Matching Strip and Tabulation Methods

The matching strip method combines the recession segments by copying them onto tracing paper and then superimposing and adjusting these horizontally until the main parts overlap. A mean curve drawn through the overlapping parts defines the MRC, as in Figure 6 (Linsley *et al.*, 1958; Toebes and Strang, 1964; Riggs, 1985). This method generally provides accurate results because visual control allows for the omission of obviously incorrect segments. If the recessions are very flat this technique has difficulty in determining where the segments fit together. Nathan and McMahon (1990) state that the matching strip method is tedious to utilise and as a result has been semi-automated to run on a computer. They found that if five to ten of the longest recessions were used these would conform to the MRC. The MRC can generally be fitted to the common recession lines with an accuracy of around 0.5 degrees.

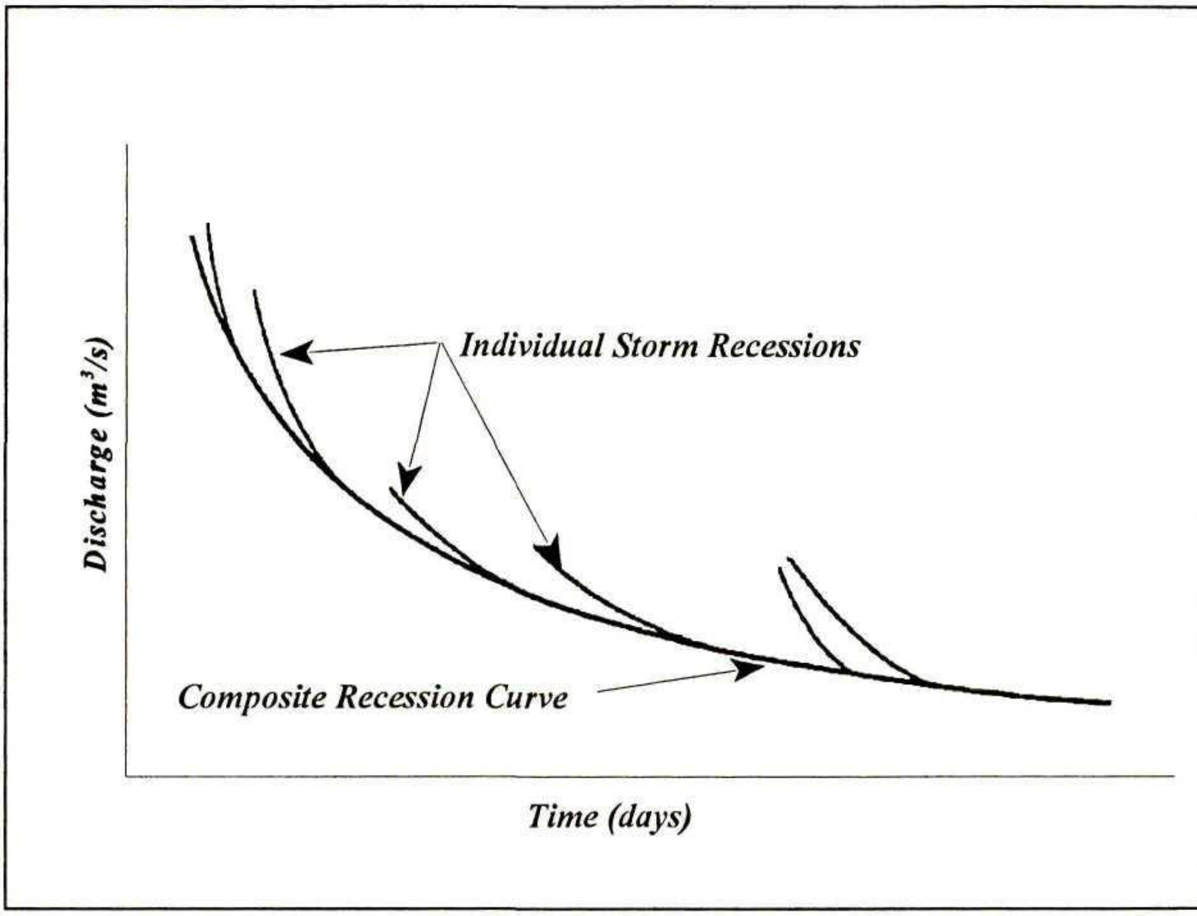


**Figure 6**: Construction of a composite recession curve using the matching strip method (After Linsley *et al.*, 1958)

The tabulation method is similar to the matching strip method except that the recession periods are tabulated in columns, as in Table 2. The columns are adjusted vertically until the initial discharges agree approximately. The average discharges are calculated for the period of record (Toebes and Strang, 1964; Hall, 1968). This method provides control in that the final curve is unlikely to be too long or too short. It does have the disadvantage that irrelevant or obviously incorrect parts of the recessions cannot be omitted without a detailed inspection (Toebes and Strang, 1964).

**Table 2 :** Example of the tabulation method using daily baseflow values from four selected recessions from the Puketurua catchment in New Zealand (After Singh, 1989)

| Baseflow Discharge ($m^3/s$) | | | | |
|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |
| August | September | July | June | Average |
| .069 | | | | .069 |
| .057 | | | | .057 |
| .054 | | | | .054 |
| .053 | | | | .053 |
| .046 | | | | .046 |
| .044 | | | | .044 |
| .043 | .043 | | | .043 |
| .040 | .040 | .042 | | .041 |
| .038 | .038 | .038 | | .038 |
| .037 | .036 | .036 | | .036 |
| .034 | .032 | .034 | | .034 |
| .032 | .031 | .032 | | .032 |
| .031 | .030 | .031 | | .031 |
| .029 | .029 | .029 | | .029 |
| | .028 | .028 | | .028 |
| | .027 | .026 | | .027 |
| | .023 | .025 | | .024 |
| | .022 | | .023 | .023 |
| | .021 | | .022 | .021 |
| | .020 | | .021 | .020 |
| | .019 | | .018 | .019 |
| | .018 | | .017 | .018 |
| | .017 | | .017 | .017 |
| | .016 | | .016 | .016 |
| | .015 | | .015 | .015 |

Butler (1967) claims that the stability of the groundwater profile will have an effect on the shape of the baseflow curve. Initial discharge may be the same for a stable and an unstable water table profile but the curves will be quite different as the unstable profile will deplete quicker. Therefore, Butler (1967) questions whether a composite hydrograph is the same as a natural baseflow hydrograph from a single long dry spell. Figure 7 illustrates Butlers (1967) contention, where baseflow curves BC and FG occur after streamflow rises A and E.

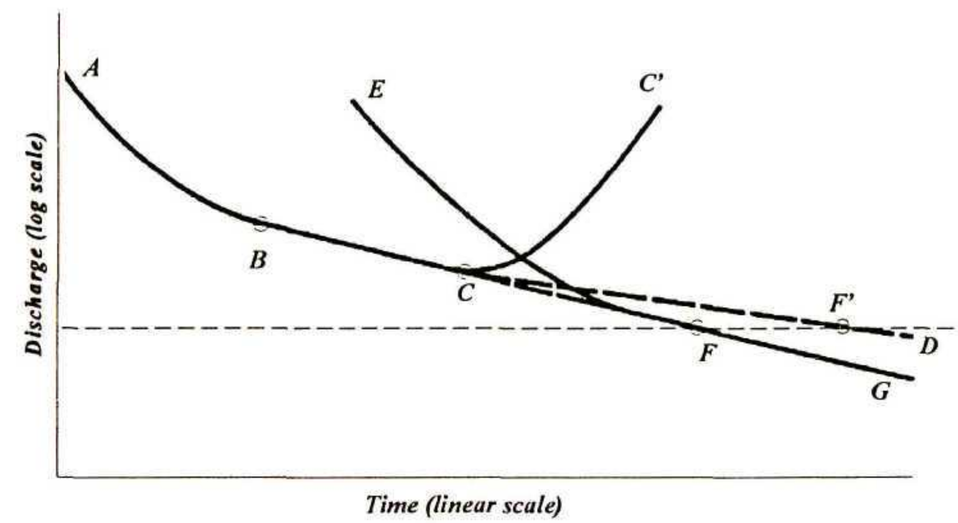


**Figure 7**: Hypothetical comparison of a composite hydrograph with that resulting from a long dry spell (After Butler, 1967)

Baseflow BC is disrupted by the streamflow rise C'. Consequently, the baseflow segment FG is pieced to the segment BC by segment CF. However, if segment BC had been allowed to drain to completion it would have drained along the segment CD. The difference in slope between the two scenarios can be seen from Figure 7.

### 4.5.3 Correlation Method

The correlation method was suggested by Langbein (1940, cited by Toebes and Strang, 1964). There are several variations of the original method and are detailed below.

The recession curve is defined by plotting, using natural scales, $Q_0$ against $Q_{0+t}$ for a specified time $t$ after $Q_0$ (Linsley *et al.*, 1958; Toebes and Strang, 1964; Hall, 1968). The data points should define a straight line which passes through the origin if the recessions are exponential. However, the points usually define a curve which becomes asymptotic to a 45 degree line as $Q$ approaches zero. Linsley *et al.* (1958) suggest that when defining the baseflow curve it is customary to envelope the data on the right as this represents the slowest recession.

Nathan and McMahon (1990) plot the discharge at one time, using natural scales, against discharge at another interval N days later during a known recession period. All points during the recession period are used, plotted and the points linked to form an arc. This process is repeated for each recession period. Equation 10 may be arranged to yield the following:

$$K = EXP(-\alpha) = (\frac{Q_t}{Q_0})^{\frac{1}{t}} \quad \textbf{(27)}$$

Hence it can be seen that the recession constant is a function of the slope of the correlation line ($Q_t/Q_0$) and the lag interval $t$.

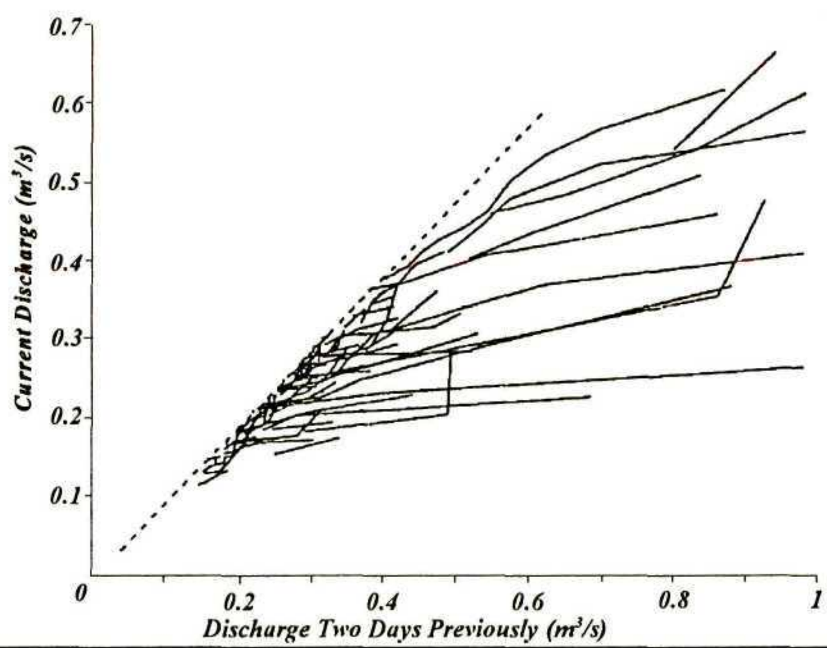


**Figure 8**: Typical master recession curve derived using the correlation method (After Beran and Gustard, 1977)

The traces of the individual recession periods generally describe an arc which becomes increasingly steeper as the flow decreases, as can be seen in Figure 8. An envelope line can be constructed along the perimeter of the region where the lines run together most densely. This enveloping line is defined as the MRC and its slope is utilised to calculate the recession constant. The Institute of Hydrology (1980, cited by Nathan and McMahon, 1990) evaluate the slope of the line at a discharge of 1/4 of the mean daily discharge. There is generally no variation in the slope of the line below approximately 2/3 of the mean daily discharge (Nathan and McMahon, 1990).

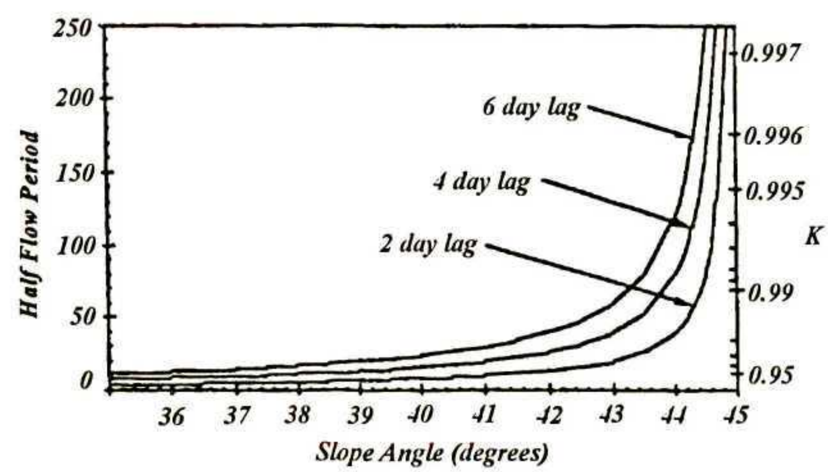


**Figure 9**: Theoretical relationship between the slope angle defined by the correlation method, the half flow period and the recession constant for different lag intervals (After Nathan and McMahon, 1990)

Toebes and Strang (1964) note that the plotting of $Q_t$ versus $Q_{0+t}$ may be undertaken on log-log paper. A straight line through the points at an angle of 45 degrees to the axes should be possible if the recessions are exponential. The slope of this line is equivalent to the log of K. This method does assume that the exponential equation fits the data selected. Riggs (1985) used this method and a *t* equal to ten days to determine a recession constant for the Buffalo River in Tennessee. Riggs (1985) converted the line of best fit into a hydrograph by beginning at a set discharge. He then determined the discharge *t* time units later. This discharge then becomes the reference to determine the following discharge a further *t* time units later. This process is continued until the curve is defined.Using Equation 29 it is possible to define the theoretical relationship between the slope angle, the recession constant and the half flow period (*cf.* Section 4.5.5), as illustrated in Figure 9 (Nathan and McMahon, 1990). It can be seen that the curves associated with the longer lag times enable a better discrimination of the recession values. Unfortunately the longer lag time excludes many of the recession periods from consideration. A compromise between the resolution and the data available has to be attained. Figure 9 also highlights one of the shortcomings of this technique. The baseflow recessions commonly lie in the range of 0.930 to 0.995. This range of values corresponds to half flow periods of 10 to 140 days. For a lag of two days this represents a difference of 3.7 degrees in the MRC. The differences for the four and six day lags are 7.4 and 10.6 degrees, respectively.

The ability to discriminate between baseflow recessions is dependent on the accuracy of the fitting of the MRC and the measurement of its slope. The fitting of the enveloping line is subjective and this subjective element may represent between 0.25 and 0.50 degrees in slope even for well defined recession curves. The error generated in estimating the baseflow recession constant with a 34 day half flow period and a lag of two days is up to +26/-10 days. The magnitude of the positive error will increase as the higher recessions are considered. Given that the baseflow ranges fall between 10 and 140 days, this is clearly an unacceptable method for such analysis.

### 4.5.4 Individual Recessions

It is possible to calculate a quantitative expression for each recession segment instead of calculating a MRC, *eg*. Chidley, 1969; Klaasen and Pilgrim, 1975; Clausen, 1992.

Brownlee (1965, cited by Bako and Owoade, 1988) derived an equation to calculate the average slope, $b'$, of $b$ regression lines fitted to $b$ blocks of observations and yields

$$b' = \frac{\sum_{i=1}^{b} \sum_{v=1}^{n_i} (x_{iv} - x_i')Y_{iv}}{\sum_{i=1}^{b} \sum_{v=1}^{n_i} (x_{iv} - x_i')^2} \tag{28}$$

Bako and Hunt (1988) reworked the equation and derived the following equation to determine a master recession constant from $b$ independent recession blocks, namely

$$LogK = \frac{\sum_{i=1}^{b}[\sum_{v=1}^{n_i} V_i y_{iv} - \frac{1}{2}(n_i)(n_i+1)(Y_i)]}{\sum_{i=1}^{b}(\frac{1}{12})(n_i^3 - n_i)} \tag{29}$$

where $b$ = number of recession blocks, $n_i$ = number of flows in recession block $i$, $V_i$ = variance of flows in block $i$, $Y_i$ = mean of the flows in block $i$, $y_{iv}$ = $v$-th flow in block $i$. It is important to account for the number of observations in each flow sequence when attempting to calculate a mean recession characteristic (James and Thomson, 1970).

### 4.5.5 Half Life

An alternative to the recession constant is the concept of the half flow period or half life. This was first suggested by Martin (1973) and is the time taken for the discharge to decrease to half of its original value. The half life is related to the recession constant by

$$H = i\ (\frac{\log\ 0.5}{\log\ K_i}) \tag{30}$$

where $H$ is the half life and $i$ is the time interval of the recession constant $K_i$ (Boughton and Freebairn, 1985). According to Demuth and Schreiber (1994) this half life has more physical meaning than the recession constant *per se* and is sensitive to the differences in recession rates of slow receding streams (Nathan and McMahon 1990). Summer recessions in Germany were found to typically have higher mean half lives than winter recessions. This difference was of the order of five days (Demuth and Schreiber, 1994). In order for Boughton and Freebairn (1985) to make comparisons between their Australian catchments and those from other parts of the world which are larger they had to make use of the half life. A significant advantage of the half life concept over the recession constant is that it eliminates the variable interval of the recession constant (*eg.* 5 minutes, 1 hour, 1 day, *etc.*) and hence brings all data to a common time unit. Similar to the half life is the log life, which is the time that it takes the discharge to fall through one log cycle.

## 4.6 LIMITATIONS OF APPLICATION TO REAL DATA

If all historical recessions conformed precisely to the proposed models, then determining a recession constant would be relatively simple. However, real data exhibits variability. It is important to consider the physical causes of this scatter.

This variation results from, *inter alia*, the following factors (Hall, 1968; James and Thomson, 1970; Klaasen and Pilgrim, 1975; Talleksen, 1995):

(a) Both the temporal and spatial variation in rainfall, moisture losses and moisture storage over the catchment may result in scatter.

(b) Further rain during some of the recessions may cause variability. A light rain may produce enough runoff to slow the recession such that after the event the recession rate is likely to increase. Reverse curvature may then also be introduced into the recession curve. Precipitation on stream channels will have an effect on the channel storage. Small rains during the recession tend to cause overestimates of the recession constant.

(c) Different relative contributions of surface runoff, interflow and baseflow between different events is likely to result in variation in the recession data set.

    This has implications for models and techniques which require some distinction between the flow components in order to establish when only, or predominantly, baseflow is present *eg*. the first three days are removed from recessions to eliminate the effects of surface runoff. These fundamental problems stem from the generality of the streamflow components model, as it is difficult to assume that additional flow components are not present in any baseflow recession. Physically, the model divides all precipitation into three broad groups which represent different durations of surface and subsurface travel time. In reality this is most likely a simplification as a continuum of flows occurs. If the sequence of flows initially included appreciable direct runoff, then the recession constant for the baseflow would tend to be underestimated.

(d) Seasonal and annual variations in the characteristics of the catchment and in the channel losses may result in scatter within the data set. These losses are problematic and occur due to evapotranspiration, underflow beneath the gauging station, vertical leakage through semi-impermeable layers and groundwater losses due to aquifer discharge outside of the catchment.

(e) Groundwater additions due to vertical leakage through semi-impermeable layers and inflow from another basin are likely to produce variable recession responses.

(f) Scatter may also be caused by not obtaining adequate flow sequences for analysis.

(g) Time variability due to human interference may also result in non-linear recession patterns. The problem normally becomes more acute as the flow decreases because the magnitude of the interference becomes an increasing portion of the total flow.

(h) The quality of the data are also very often a limiting factor. The accuracy, and indeed frequency of the flow measurements may restrict the processes that can be studied. Rounding error may also be a problem, for example, rounding may result in the same discharge for a number of days before flow decreases sufficiently that a lower value is recorded. Correlated measurement errors may also produce unusual recession constant values. Short sequences which begin with relatively low daily flow values seemed to yield poor recession constants, partly due to the fact that the records do not reflect a high instrument precision at low flows.

A similar problem is encountered when one attempts to fit simple linear models to observed data. The straight line plot of the simple exponential model on semi-log paper does not apply to many baseflow recessions. A linear plot is generally attained when hydrogeological conditions are simple (Ineson and Downing, 1964). However, actual data when plotted on semi-log paper usually produce a curve. The complete baseflow recession curve in semi-log plot may have an initial steep slope which gradually decreases to produce a flatter portion (Linsley *et al.*, 1958; Nutbrown and Downing, 1976). Finally, although this is generally only seen in ephemeral streams, or in regions with a prolonged dry period, there may be a further steep portion as the stream dries up (Nutbrown and Downing, 1976). Consequently, many investigators have concluded that no single linear plot can be constructed to describe baseflow recession (Nutbrown and Downing, 1976; Anderson and Burt, 1980; Petras, 1986; Nathan and McMahon, 1990).

The non-linearity of the plots is ascribed, inter alia, to the following factors (Barnes, 1939; Ineson and Downing, 1964; Kilpatrick, 1964; Hall, 1968; Singh, 1968; Singh, 1969; Singh and Stall, 1971; Nutbrown and Downing, 1976; Riggs, 1985; Bevans, 1986; Nathan and McMahon, 1990; Simmers, 1996):

(a) There may be carry-over from previous recharge events.

(b) Frequent recharge events may be a problem in humid regions as it has been shown that pulses of recharge may induce a non-linear response from an aquifer.

(c) Discharge within mountainous regions is likely to be fed, in part, by soil moisture which appears to drain non-linearly. This would imply that the total streamflow is likely to be non-linear too.

(d) It has also been suggested that the area supplying baseflow may not be constant.

(e) Spatial variations in recharge as well as channel, bank and floodplain storage along with variations in evapotranspiration may produce non-linear responses.

(f) The presence of other flow components may result in a non-linear recession.

(g) Non-linear recessions may be produced by multiple sources of flow. A stream, may, in nature may be fed by a number of aquifers. These aquifers may have different discharge characteristics and different rates and times of recharge. Combinations of linear sources such as a large artesian aquifer with a long response time and a water table aquifer with a short response time will yield non-linear recession curves. Alternatively, these sources of baseflow may represent an unconsolidated alluvial aquifer in addition to the bedrock aquifer. Following recharge, the initial baseflow may be controlled by the unconsolidated aquifer and once this has drained, the recession curve is controlled by the bedrock aquifer. Non-linearity may also occur where rivers receive contributions from different springs draining independent fracture systems with very different decay rates. Several researchers have also recognised that sources other than groundwater could have an influence on the shape of the baseflow recession. These sources include lakes, marshes, snow and ice, channel and bank storage.

(h) Most catchments have a complex geology and the streams draining such catchments may have an incomplete hydraulic continuity with the underlying aquifers. These conditions could result in non-linear baseflows.

(i) The thickness of the aquifer and the depth of stream entrenchment into the aquifer have an impact on the linearity of the recession. Singh (1968; 1969) and Singh and Stall (1971) plotted baseflow recession curves on a system of dimensionless axes. They note that for idealised boundary conditions of a fully penetrating stream the plot is generally a curve. It has been noted by Ineson and Downing (1964) that the baseflow recessions of many rivers in the UK which do not fully penetrate the aquifer plot as curved lines on semi-log paper.

(j) The decay of piezometric heads cannot be truly represented by a single exponential expression, as dynamically the groundwater system is very complex and is likely to be under constantly varying heads. Consequently, non-linear baseflow recession may result.

(k) Non-linearity may also be caused by factors which are not accounted for in the mathematics expressing the baseflow recession.

(l) While not a factor affecting the linearity of the semi-log plot, many of the difficulties in applying a linear model arise from the assumptions which are inherent in the mathematical equations used. The equations are derived for flow from a single source which is generally of a unit width and under conditions of no recharge. The storage unit is filled by recharge and then allowed to drain without interruption or change. The natural system is not as simple and all of the assumptions may be questioned.

Despite these observations to the contrary, the simple exponential model remains the most widely used analytical technique for baseflow recessions. Hence, a linear model for recession is assumed by all of these researchers, even though the groundwater dynamics of even the simplest of aquifers may behave in a non-linear fashion. The reasons for this gross assumption are varied (Hall, 1968; Nathan and McMahon, 1990; Talleksen, 1995) and summarised below:

(a) It is desirable to utilise a catchment parameter which will reflect the rate at which streamflow diminishes in the absence of groundwater recharge.

(b) The form of the equation allows a simple and generally consistent means of deriving a single unknown parameter. Expressions with a single constant are preferable, as it may be difficult to assess the relative importance of two or more parameters. However, these equations with more than a single parameter generally provide a better fit to the data than those with a single parameter

(c) The ease of construction and use of the semi-log plots to determine a recession constant is probably the most common reason for their use.

(d) The derived constants provide a simple means of comparing the recession characteristics of different catchments.

(e) The derived constants provide a useful tool for practical application in analysis and design.

(f) More sophisticated models have failed to always improve on the accuracy of simple predictive models like the simple exponential model. For large catchments where the conditions are complex there is little justification for using more complex relationships.

(g) The method is useful in that a change in the value of the recession constant suggests a change in the flow regime, which is not always the case when dealing with other types of recession equations.

Nathan and McMahon (1990) conclude that when one considers the requirements of regionalisation and prediction and the fact that more sophisticated models have failed to improve on the accuracy of simple models, it would appear that it is justifiable to adopt a simple single source model of exponential recession. However, they also note that it must be appreciated that adoption of a single source exponential recession model must be viewed merely as a predictor of catchment geomorphology that is indicative of low flow characteristics.

It is clear that there are still many problems with recession analysis (Hall, 1968). Computers have, however, allowed for the development of automated and objective analytical methods which have, to a degree, removed some of the subjectivity and have encouraged a wider use of the analyses.

# 5. RESEARCH OBJECTIVES

The objectives utilised during the course of this study are detailed in this Chapter while the methodologies employed in order to achieve these are described in Chapter 6.

## 5.1 RESEARCH HYPOTHESES

In order to avoid biasing the research by proposing hypotheses at the outset, a broad set of aims was first established to provide research direction. These aims were as follows:

Aim 1: Establishment of a streamflow database.

Aim 2: Construction of master recession curves which are composed of multiple segments. This would aid in the determination of the true shape of the master recession curves. McMahon (1995) stated that exponential recession theory had been inappropriate for modelling baseflow recession in Australia and he believed that a similar result would be achieved in South Africa. Hence it was necessary to ascertain whether this was indeed the case, as it has serious implications for the modelling of baseflow recession and the simplifying assumptions adopted during the course of research.

Aim 3: Attempt to explain the patterns defined by the master recession curves in terms of the various factors which affect baseflow. This would hopefully elucidate further the relationships between the various factors and baseflow, as well as identifying those specific factors affecting baseflow which are of importance in South Africa.

Aim 4: Investigate the feasibility of establishing a Rule Based Model for baseflow recession. McMahon (1995) suggested the development of such a model as it overcomes many of the simplifying assumptions that are reminiscent of this type of research and is a realistic representation of what the data are actually illustrating.

The steps which were followed in order to achieve these aims are outlined in the following Sections and in Chapter 6.

## 5.2 ACCOUNTING FOR THE FACTORS WHICH AFFECT BASEFLOW

Aforegoing chapters have reviewed the many and diverse factors which are likely to have an effect on baseflow recession. During the course of this research these factors had to be borne in mind and methods for eliminating their effects had to be devised. Those factors that could not be eliminated had to be used in conjunction with the data in order to explain the patterns of the MRCs which were derived. The previous literature reviews provided the foundation and objective grounds for the selection of the variables used. The manner in which the various factors were eliminated or accounted for is outlined below.

### 5.2.1 Climate

In order to account for the variable inputs into the catchments a number of climatic parameters are used (*cf.* Section 3.1) . These, on the whole, are readily obtainable and include the Mean Annual Precipitation (MAP), the rainfall concentration and the rainfall seasonality. While these variables indicate the inputs into the system they do not provide an indication of the amount of water which actually recharges the groundwater. Hence, two independent measures of groundwater recharge are determined.

### 5.2.2 Subsurface Geology

The proportion of each lithology within each catchment is derived (*cf.* Section 6.6.2). This lithological classification accounts for rock type, lithological age, presence of structure and degree of metamorphism. An index based on these geological characteristics is developed (*cf.* Section 6.6.3.2) and used to explain the patterns defined by the master recessions curves which have been derived.

### 5.2.3 Surficial Geology

It was originally anticipated that the types of soils present within each catchment along with their ability to store and transmit water laterally could be determined (*cf.* Section 3.2.2.1). This information is, however, not readily available and hence it had to be assumed that the effects which soils have on baseflow are adequately represented by the subsurface geological information together with the average catchment slope.

### 5.2.4 Basin Morphology

The three variables chosen to describe basin morphology are catchment size, drainage density and average catchment slope (*cf.* Section 3.3.2). Catchment size was chosen as the descriptor of input and storage of water within the catchment. Drainage density was used as a measure of the lateral travel distance and time of both the surface and subsurface runoff. Average catchment slope was included to account for its influence on lateral travel times. This information will be used to explain the patterns defined by the master recessions curves which have been derived.

### 5.2.5 Evapotranspiration

All recessions are broadly classified as either summer or winter (non-summer) recessions. This will indicate whether there is a fundamental difference between the two broad seasonal classifications (*cf.* Section 3.4). It is assumed that evapotranspiration rates are low during the winter period when compared with those of the summer period and that the master recession curves derived for this season are therefore reasonably close to the actual baseflow recession.

### 5.2.6 Bank Storage

Of all of the factors which affect baseflow recession, this is the most difficult to assess or quantify. It is suggested that determination of this factor on an individual catchment basis is the only means of determining its presence and degree of influence. Owing to the number of catchments under investigation, such an analysis is beyond the scope of this study. Consequently, for the purposes of this research, bank storage had to be assumed to be negligible or not present for the catchments under consideration despite the fact that this factor is potentially of great importance in the semi-arid and arid regions of South Africa (*cf.* Section 3.5).

### 5.2.7 Anthropogenic Influences

It is important to account for the effects of humans on the hydrological system (cf. Section 3.6). The catchments selected are located upstream of major impoundments and points of abstraction and are thus considered to exhibit natural streamflow. Catchments which have undergone major land use changes are not included in the data set. All catchments have been statistically tested to ensure that their streamflow records are homogeneous (*cf.* Section 6.1.1).

## 5.3 ADOPTED RECESSION SELECTION CRITERIA

The literature review on previous modelling approaches highlighted many different techniques and criteria which should be used when attempting to select hydrograph recession limbs for baseflow recession analysis (*cf.* Section 4.3.1). Those criteria which have been adopted for the present research are outlined below. Where specific modifications to those criteria are suggested, supporting evidence for the modification or mode of action is also detailed.

(a) The recession was defined by successive decreasing values of daily streamflows.

(b) The recession ended when the streamflow values began to increase again, the streamflow fell below 0.1 $m^3.s^{-1}$ or when appreciable rainfall was noted within the catchment.

Visual investigation of semi-log plots of baseflow recessions indicated that below 0.1 $m^3.s^{-1}$ the recessions were generally not conforming to expected trends and tended to taper off. An example of this tapering off of streamflow values is illustrated in Figure 10 below. It is believed that this was indicative of a lack of sensitivity of the streamflow recording equipment at increasingly lower flows. This is borne out by the fact the DWAFs operational weirs are generally U-notch weirs which do not have sharp and distinct metal edges often present at weirs in research catchments. This factor thus introduces a degree of inaccuracy, particularly at low streamflow values. No recession in a time series during which appreciable rainfall occurs was accepted as this was likely to have an effect on the shape of the recession curve by introducing flow components other than baseflow. Appreciable rainfall is here defined as 10mm of rainfall or greater per day. Schulze

(1995b) suggested that this threshold of rainfall provided a realistic cut-off point between those recessions which were acceptable and those which were not acceptable owing to the presence of other runoff components.

(c) The minimum acceptable duration of a recession was 10 days. The recession was required to be of this length to ensure that when the first three days were removed from the recession to eliminate the effects of non-baseflow components it was, at least, of seven days' duration.

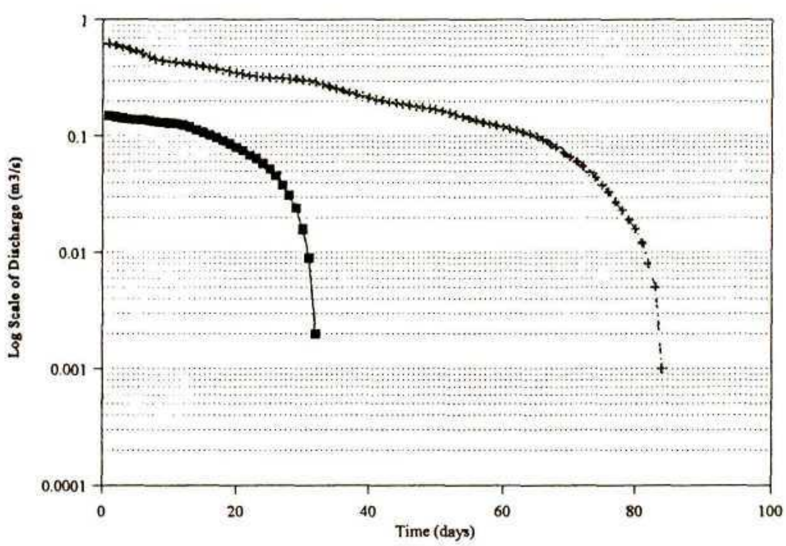


**Figure 10**: Semi-log plots of streamflow indicating the apparent inaccuracy of the measurements below 0.1 $m^3/s$ for catchments A3H001 (squares) and A4H002 (crosses)

(d) The first three days of each recession were removed to eliminate non-baseflow components.

In order to test that the removal of the first three days from the recession held some scientific merit and was not merely an arbitrary "rule of thumb", a test was performed using the digital filter proposed by Nathan and McMahon (1990). They proposed a simple recursive digital filter of the type given in Equation 31.

$$f_k = \alpha f_{k-1} + \frac{(1+\alpha)}{2}(y_k - y_{k-1}) \quad \textbf{(31)}$$

where $f_k$ is the filtered quick response at the *k*-th sampling instant, $\alpha$ is the filter parameter and $y_k$ is the original streamflow. The filtered baseflow is thus defined as $y_k - f_k$.

Nathan and McMahon (1990) compared their separation technique with other techniques and found that their technique provided results which were not only equally as reliable but was far quicker to apply and less subjective than the other techniques. Nathan and McMahon (1990) found that a filter parameter of between 0.90 and 0.95 provided the best results.

Several Sections of streamflow hydrograph for several stations were filtered using the digital filter equation given in Equation 31 where a filter parameter of 0.925 was used with a single recursion. The results were plotted graphically. An example of the type of results obtained is given in Figure 11 where it will be noted that the baseflow component generally rejoins the streamflow hydrograph recession limb three to five days after the peak of the event.

This observation was both reproducible not only for different portions of an individual station's record, but for different stations as well. Hence the assumption that the removal of the first three days' discharge would remove the majority of the non-baseflow components was regarded as being reasonable.

(e) No recession containing data which were flagged with any querying or suspect data flag was acceptable.

(f) No recession containing more than two equal and successive streamflow values was acceptable.

It was assumed that these successive days of equal streamflow values most likely indicated an error of some sort. These sources of error could include a faulty pen on the recording gauge, obstructions in the weir notch, such as jammed logs, and anthropogenic influences (Schulze, 1995b).

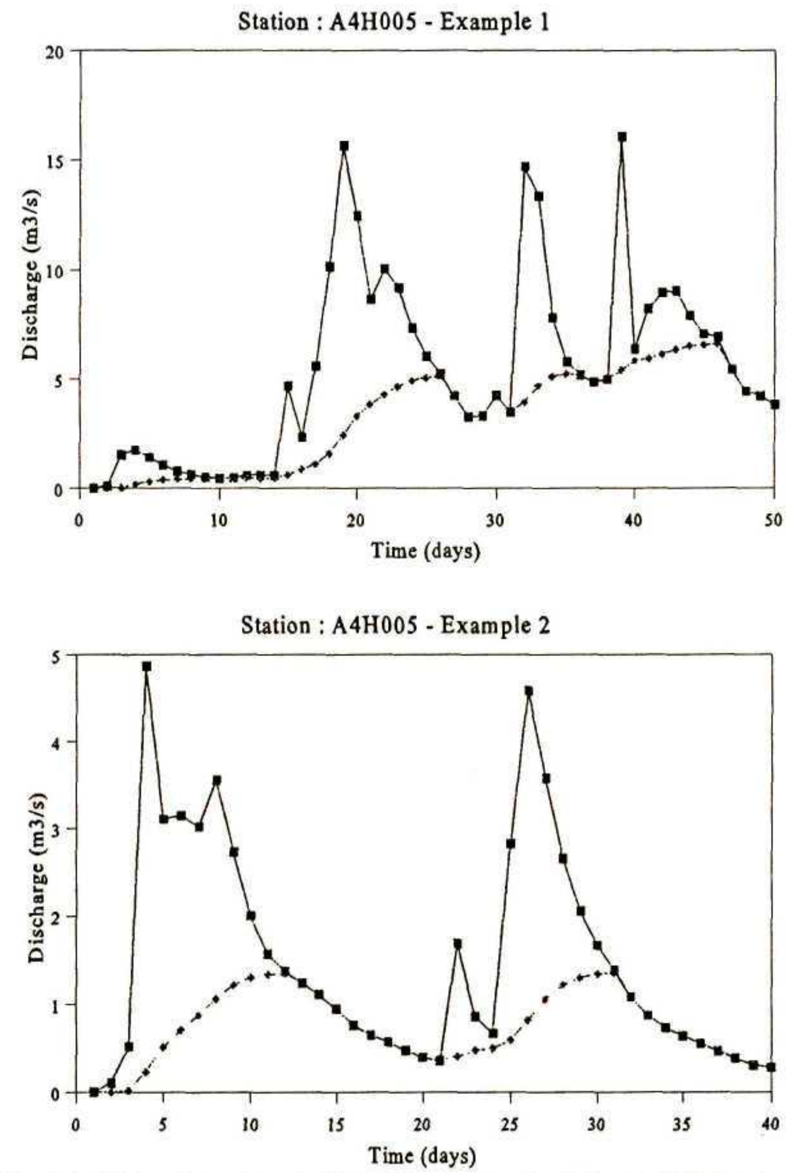


**Figure 11**: Examples of hydrographs with the filtered baseflow (diamonds) and total flow (squares) values indicated

These recession selection criteria were used in the various computer programs described in the following Section.

# 6. METHODOLOGIES EMPLOYED IN THE ANALYSIS OF BASEFLOW RECESSION

This chapter outlines the methodologies utilised in the selection and analysis of the streamflow data for the purpose of characterising baseflow recession.

## 6.1 SELECTION OF SUITABLE GAUGING WEIR DATA

Three factors were considered when attempting to locate and select suitable gauging weir data, these being the availability of the data, the catchment size and the quality of the data. The data had to be freely available and be representative on a national scale over a variety of catchment sizes and rainfall regimes. Initially the only restrictive parameter placed on the catchment size was a minimum catchment area of 1 $km^2$. Smaller catchments were not considered as obtaining representative catchment characteristics for these catchments using the techniques described below is difficult.

To establish the trends of baseflow recession one has to select gauging weirs which are relatively representative of the natural system and are not affected significantly by anthropogenic factors. Such anthropogenic factors include, *inter alia,* abstractions, additions of effluent, the presence of dams and land use changes. The presence of natural features such as wetlands within the catchment may produce effects similar to those of a dam resulting in attenuation of flood peaks and enhancement of baseflows. Catchments which were found to contain wetlands or similar natural structures were thus deemed unsuitable for the present study.

### 6.1.1 Department of Water Affairs and Forestry Gauging Weirs

The Department of Water Affairs and Forestry (DWAF) have compiled a list of every gauging weir which it manages within the Republic of South Africa (DWAF, 1990). In response to research undertaken by King and Tharme (1994) the DWAF compiled an abbreviated list of gauging weirs which were located upstream of major impoundments and abstractions and had a minimum record length of 20 years. Joubert and Hurly (1994) verified the position of these gauging weirs relative to major impoundments by checking maps. In total, 352 gauging weirs were selected. Joubert and Hurly (1994) then performed homogeneity tests on the selected gauging weirs to ensure that there were no changes in the flow pattern with time. This was achieved by using double mass plots.

Dent, Lynch and Tarboton (1990) defined 712 homogeneous climate zones where each was represented by a specific rainfall station. The closest of these 712 rainfall stations to the selected weirs was assigned as the source of the rainfall component for the double mass plots, which entailed the plotting of cumulative monthly flows against cumulative monthly rainfalls. These plots were assessed visually for breaks in slope which most likely indicated non-homogeneity, and when these occurred the stations were flagged and removed from the data set. The remaining stations were assumed to be recording natural flows.

The 201 gauging weirs assumed to have a homogeneous streamflow record were obtained from Joubert (1995) and used in this baseflow recession study. These gauging weirs are listed in Appendix 1.1.

### 6.1.2 Other Sources of Streamflow Data

To ensure that as many gauging weirs as possible were utilised in this study, sources of data other than the DWAF were investigated.

The DAE at the UNP maintain a number of gauging weirs in their Cedara and DeHoek/Ntabamhlope research catchments. It was hoped that these would provide further sources of reliable streamflow data. Only one of the Cedara catchments was chosen for the study as it qualified in regard to the initial catchment size parameter of 1 $km^2$. None of the DeHoek/Ntabamhlope catchments were selected, primarily due to land use changes which include afforestation and the development of informal settlements. Other factors considered at DeHoek/Ntabamhlope were the presence of a relatively large wetland upstream of many of the catchments along with the relatively small catchment sizes. The one UNP DAE gauging weir is listed in Appendix 1.2.

The Council for Scientific and Industrial Research (CSIR) maintains a number of gauging weirs in the Cathedral Peak area. Of these only four are larger than 1 $km^2$ in size and of these four, two have undergone radical land use change (*viz.* afforestation) over a number of years making them unsuitable for this study. Despite the fact that the data from the remaining two stations were deemed suitable for this study they, were effectively unavailable due to financial strictures which prevented the purchase of these data.

## 6.2 AUTOMATED SELECTION OF SUITABLE BASEFLOW RECESSIONS

A *Fortran 90* program, named DWAFREC.F90, was written to extract recessions from the streamflow record for each of the selected gauging weirs. The program utilised the criteria outlined in Section 5.3 which had been established primarily from the literature, although general rules of experience were also utilised. A simplified flow diagram describing the logic employed by the program is illustrated in Figure 12. The steps illustrated in the flow diagram in Figure 12 are each described below:

(a) The streamflow record is scanned, a recession is determined to be taking place and is extracted from the streamflow hydrograph.

(b) All extracted recessions are checked further to ensure that they are longer than or equal to 10 days in duration.

(c) Each recession is checked to ensure that it contains no missing or suspect data.

(d) Recessions which are longer than 20 days in duration are permitted to have up to and including three days of suspect data provided these do not occur on days one to three of the trimmed recession. This technique was employed as perfectly good recessions of considerable length were being excluded due to odd days of missing or suspect data. Hence it was felt that, provided the recession was sufficiently long, these recessions would be acceptable as the introduction of error is unlikely to be significant. These missing days of data would be infilled by interpolation and hence the missing days could not be at the beginning of the recession.

(e) The first three days are removed from the recessions to remove non-baseflow components of streamflow.

(f) All streamflow values of less than or equal to 0.1 $m^3.s^{-1}$ are removed from the ends of each recession.

(g) Recessions which contain more than two successive streamflow values which are equal in magnitude are excluded. However, if more than seven days of streamflow occur before the equal values, then these are extracted as they occur before the introduction of possible error.

(h) Recessions of longer than 20 days in duration and which contain up to three days of suspect data have suspect data values infilled. This is achieved by assuming that the recession occurs at a constant rate between the flow values which are assumed to be correct and replacements for the missing streamflow values are thus interpolated.

(i) The selected recessions are classified into two groups, namely summer and non-summer recessions. The summer recessions occur during the months of December through May while the non-summer recessions occur during the remainder of the year. These seasonal classifications are consistent with those described in Section 6.6.1.2.

(j) DWAFREC.F90 requires rainfall data for the final stage of recession selection (*cf.* Section 6.3). The rainfall data is used to ensure that no significant rainfall occurs during any recession selected to this stage as this may result in non-baseflow components which will distort the baseflow recession and possibly introduce error if included. However, if more than seven days of streamflow occur before the onset of significant rainfall (*ie.* >10mm) then these are extracted as they occur before the introduction of possible error.

(k) All of the recessions selected to this stage are checked to ensure that they are still of, at least, seven days in duration. All recessions which are shorter are eliminated.

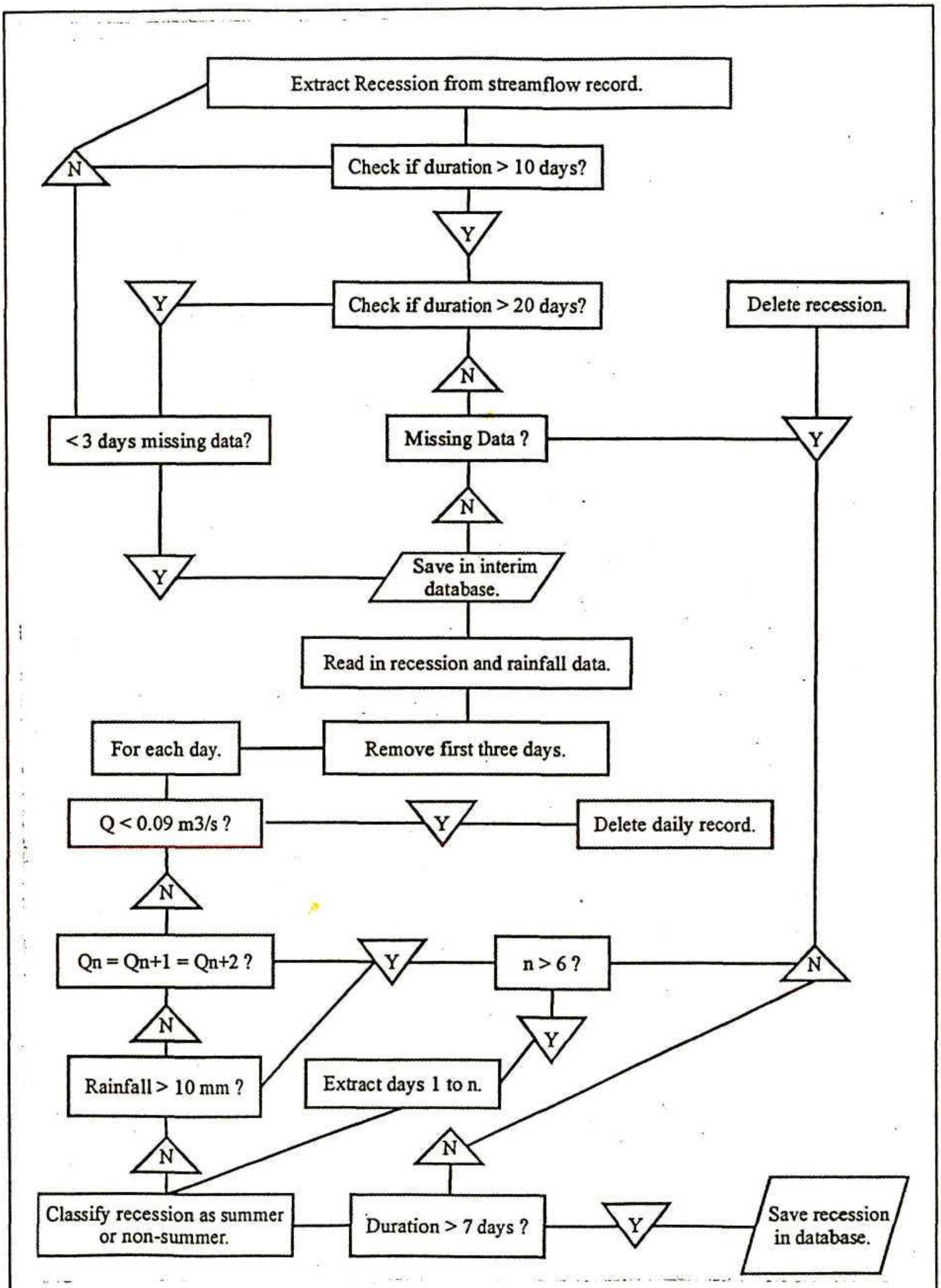


**Figure 12**: Flow diagram describing the algorithms utilised in DWAFREC.F90

## 6.3 ASSIGNING A RAINFALL STATION TO EACH GAUGING WEIR

DWAFREC.F90 requires rainfall data for the final stages of recession selection for each catchment. The catchments were each assigned driver rainfall stations using the *ARC/INFO* Geographical Information System (GIS) in the following manner:

(a) The one minute by one minute of a degree latitude/longitude Mean Annual Precipitation (MAP) grid (*cf.* Section 6.6.1.1) was used as the background upon which the quaternary catchment boundaries, the provincial boundaries, rivers, gauging weirs and rainfall stations were plotted.

(b) All rainfall stations which are currently operational were reselected and coloured a different colour to the remaining stations. K. Meier (1995) developed a rating for each daily raingauge record in South Africa based upon the quality of its data and length of record and this was used to reselect all rainguages with a rating greater than a specific threshold. All stations with a rating of greater than zero are deemed to have reasonably good data. These rainguages were, once again, coloured a different colour;

(c) Each catchment was then visually assigned a driver rainfall station by attempting to ensure that the assigned rainguage was not only within the same MAP zone and relatively near to the gauging weir but within the same quaternary catchment, preferably upstream of the gauging weir, had the same period of record as the gauging weir and was both currently operational and attributed a ranking above the threshold.

The rainfall stations derived in this manner were considered more representative than those generally selected by Joubert and Hurly (1994) owing to the greater number of rainguages considered and the more detailed selection criteria utilised. The rainfall data utilised in DWAFREC.F90 had to be checked and all missing or suspect data were replaced by a "patched" (*ie.* synthetic) value. This patching was considered unlikely to influence the quality of the recessions extracted from the streamflow record. In fact it introduced more rain days and hence resulted in the rejection of more recessions. The rainfall station records were patched using a Fortran 77 program written by Meier (1995) and named RAPID (RAinfall Patching using Inverse

Distance weighting). This program creates the patched data from surrounding stations and was used by Meier (1995) during the establishment of the DAE's Quaternary Catchment Rainfall Database.

## 6.4 DETERMINING THE RAINFALL REGION FOR EACH GAUGING WEIR

A further complicating factor is the seasonal distribution of rainfall received by the catchments selected for the study. Since winter and summer rainfall regions receive most of their rainfall in different seasons, it became clear that the proposed summer and non-summer classifications were inadequate and that a more correct classification of rainy and non-rainy season was required. Hence it was necessary that each gauging weir be classified according to the annual rainfall distribution region into which it falls.

The rainfall seasonality classification for South Africa developed by Schulze (1996) at a one minute by one minute of a degree lattitude/longitude was used in this study. The rainfall seasonality was calculated using the Markham (1970, cited by Schulze, 1996) technique described in Section 6.6.1.2 on rainfall concentration. The "all year" region was delineated first by analysing the median monthly rainfall at each of the 437 000 grid points. All points with a rainfall concentration of less than 20% were designated as "all year" rainfall regions. The winter rainfall regions were identified by applying a smoothed percentages index (Schulze, 1996). In this index the median monthly rainfall is expressed as a percentage of the monthly rainfalls and then subjected to a weighted smoothing by considering the months on either side, to produce Equation 32 which expresses the monthly percentage, $P\%$, as

$$P\% = \frac{1}{4}(P\%_{i-1} + 2P\%_{i} + P\%_{i+1}) \quad \textbf{(32)}$$

where $i$ = months (1 to 12). The winter rainfall region grid points are those which exhibit a smoothed percentage index of greater than 8% during the months of June, July and August. Most of South Africa, however, falls into the summer rainfall regions. The smoothed percentages technique was again applied except this time the region was classified as "early" summer if the peak occurred in December or earlier, as "mid" summer if in January, as "late" summer if in February and as "very late" summer if in March to May (Schulze, 1996).

A *Fortran 90* program called SEASLAT.F90 was written and used to match the gauging weir co-ordinates with the nearest grid point co-ordinates for which there was a seasonal classification. Using this information a uniform classification of rainy and non-rainy seasons was attained for all of the gauging weirs regardless of the time of year that each station receives the majority of its rainfall.

## 6.5 MANIPULATION OF SELECTED RECESSIONS

In order to establish multiple segment MRCs a new approach had to be established. Exponential recession theory is generally used when researching baseflow recession, mainly because of its ease of application. However, there have been many problems applying this theory in practice, particularly one of poor fit. Several researchers have attempted to fit more than one line segment to the recession in order to improve this fit *eg.* Barnes, 1939; James and Thomson 1970; Federer, 1973. Many of these techniques still require the assumption of linearity of the semi-log plot in order to be successful. The technique developed by Federer (1973) was adapted for the purposes of this study where an objective technique averages recession constants of short segments of the recessions curves. Federer's (1973) technique divides each recession into 1-day segments. These segments are close enough to being linear in semi-log plot that a recession constant can be calculated for each. The mean recession constant was then calculated for each group of segments. The average recession is then constructed by joining, end to end, each of the straight line segments for each date category and had a slope equal to the mean recession constant for that category (Federer, 1973). This technique was adapted for the current study. Federer (1973) calculated average values for each date category, however, for the current study the average recession was to be calculated for discharge ranges. This overcomes the different initial discharges for each recession by assuming that different recessions will recede at similar rates within the same discharge range (*cf.* Figure 14).

The recessions selected and saved by DWAFREC.F90 for each gauging weir were used as input to a *Fortran 90* program that was written and called INVERT.F90. This program takes each of the recessions and converts these data points to a different format. Before conversion the data are stored as daily values of stream discharge. The current study requires the calculation of a recession constant for each interval of discharge, for example, between 5 and 6 $m^3.s^{-1}$. To allow for this calculation the data has to be converted from daily specific values to discharge specific values. This is best illustrated with the use of Figure 13 where the dashed lines indicate an example of the original daily specific data. The curve may however be described in terms of whole values of discharge. The solid lines indicate an example of discharge specific data. Each recession for each gauging weir was converted from daily specific to discharge specific format. For discharge values above 2 $m^3.s^{-1}$ the increment for each discharge interval was 1 $m^3.s^{-1}$. However, discharge values below 2 $m^3.s^{-1}$ generally define a very shallow curve and whole discharge intervals are unsuitable to describe such a curve as the sample spacing is too coarse. As a result an increment of 0.1 $m^3.s^{-1}$ was used for all discharge values of less than 2 $m^3.s^{-1}$.

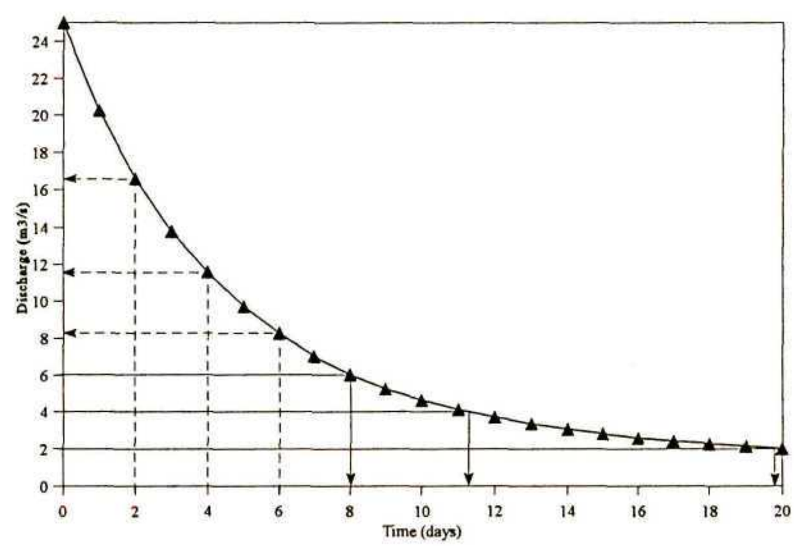


**Figure 13**: Illustration of the daily (dashed) and discharge (solid) specific data describing the same recession curve

A recession constant was then calculated for each discharge interval for each recession. A weighted average of these recession constants for each discharge interval was then calculated as illustrated in Figure 14. These average recession constants for each discharge interval define a slope between two known discharge values and as such were used to define the Master Recession Curve (MRC). This technique not only produces a multiple segment MRC but represents an objective manner in which to utilise a stations complete streamflow record for the calculation of this MRC. Not all of the gauging weirs produce MRCs due to the strict criteria laid down for the selection of acceptable recessions and as such were eliminated from the study. The gauging weirs either did not produce acceptable recessions at all or they produced too few for the MRC to be statistically meaningful. However, of the gauging weirs which produced a MRC some only produce a MRC for the wet season and not for the dry season or vice versa. These various results are summarised in Appendix 2.10 and are discussed further in Section 7.4.3.

The MRCs for each of the remaining gauging weirs were plotted in semi-log format to determine if they define a straight line and therefore conform to exponential recession theory. In order to plot all of the MRCs on the same system of axes that these may be overlain for comparison purposes the results had to be converted back to daily specific format and had to be area normalised such that the discharge was per km$^2$ of catchment area. The patterns defined by these final MRCs were then explained in terms of various catchment characteristics (*cf.* Section 7.5)

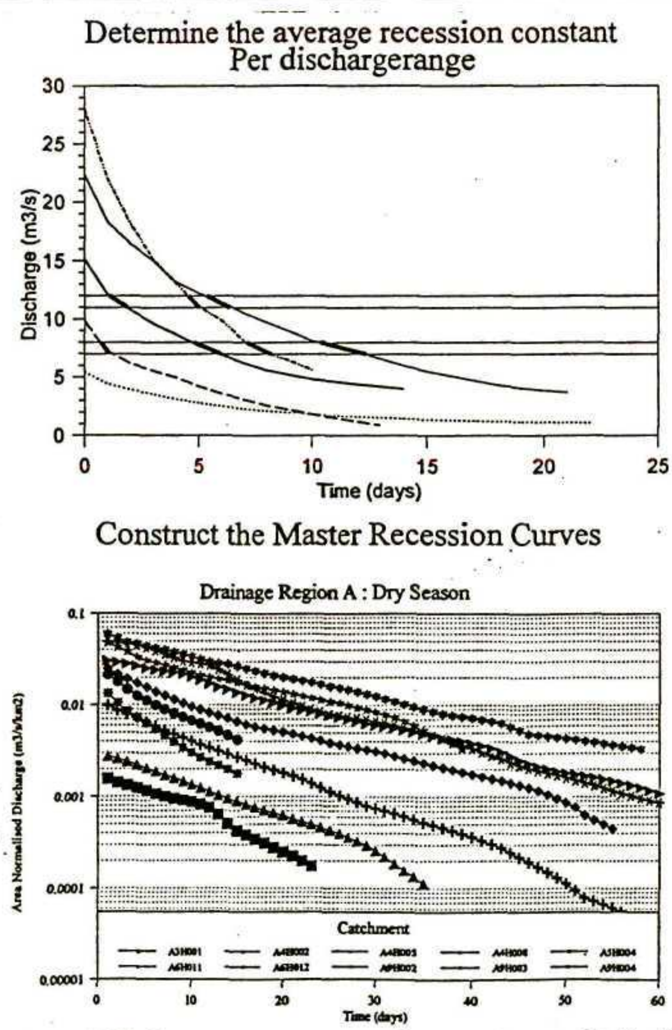


**Figure 14**: Illustration of the process of determination of a master recession curve

## 6.6 DERIVATION OF CATCHMENT CHARACTERISTICS

Various catchment characteristics were required to explain the patterns defined by the MRCs. At the outset a limited set of catchment characteristics was selected, namely, MAP, rainfall concentration, rainfall seasonality, estimates of groundwater recharge, a geological index, catchment area, average catchment slope and drainage density. These various parameters were derived in the following manner.

### 6.6.1 Climatological and Recharge Variables

The likelihood of groundwater recharge occurring and estimates of this recharge were included in the study as the amount and timing of recharge is likely to have a significant effect on the baseflow recession behaviour of a catchment. The MAP and rainfall concentration values were used as indicators of the likelihood of recharge taking place. The estimated values of recharge were obtained from two different studies and are compared in Section 7.3.3

#### 6.6.1.1 Mean annual precipitation

The MAP characterises the quantity of water that is available within a region. The MAP is likely to affect baseflow in that, in general, a region which has a higher MAP is more likely to experience groundwater recharge than a region with a lower MAP.

Dent, Lynch and Schulze (1989) divided South Africa, Lesotho and Swaziland into 34 regions which they considered to be relatively homogeneous in terms of the factors affecting seasonal rainfall distribution. These factors included altitude (including the influence of orographic uplift), distance from the sea (as an index of continentality), aspect, terrain roughness and direction of prevailing rain bearing winds along with other variables. Data from over 6000 rainfall stations were then utilised to develop equations to determine MAP for each of these 34 regions. From this information a one minute by one minute of a degree lattitude/longitude grid of MAP was generated.

This MAP grid, illustrated in Appendix 2.1, was used as input to the zonal statistics procedure, detailed in Section 6.6.4, from which the average of the grid point MAPs was calculated for each catchment.

#### 6.6.1.2 Rainfall concentration

Rainfall concentration is a measure of the annual distribution of an areas rainfall and is likely to have an effect on the recharge which reaches an aquifer. Several days of rainfall or a number of closely spaced events are generally required to overcome the many losses and deficits which are likely to occur as rainfall infiltrates and makes its way towards the groundwater system. Hence one would expect a catchment which receives the majority of its rainfall in a shorter space of time to experience more groundwater recharge.

Schulze (1996) calculated a rainfall concentration index using a set of equations known as Markham's (1970, cited by Schulze, 1996) technique. This technique is based on the vector representation of mean monthly rainfall totals. The vector is defined in magnitude by the amount of rainfall while the direction is defined by the month of the year expressed in units of arc. The monthly vectors are added to produce a result whose direction defines the month in which the rainfall is most concentrated while the magnitude, when divided by the MAP, gives a "Precipitation Concentration Index" (PCI). If the PCI approaches 100% this implies that the years rainfall received at the location in question is highly concentrated within a single month while a value near 0% implies that the rainfall for each month is similar (Schulze, 1996).

A one minute by one minute of a degree lattitude/longitude grid of rainfall concentration, containing over 437 000 values, was constructed by the DAE at the UNP during the preparation of the Southern African Atlas of Agrohydrology and Climatology (Schulze, 1996). The grid, illustrated in Appendix 2.2, was used as input to the zonal statistics procedure, detailed in Section 6.6.4, where the average rainfall concentration was calculated for each catchment.

#### 6.6.1.3 Rainfall seasonality

The rainfall seasonality was also considered as the time of year during which a catchment receives the majority of its rainfall is likely to have an effect on the groundwater recharge. For example, a summer rainfall region is likely to experience high ET losses during its rainfall season and this may have an impact on the amount of water that reaches the groundwater zone.

A one minute by one minute of a degree lattitude/longitude grid of rainfall concentration, containing over 437 000 values, was constructed by the DAE at the UNP during the preparation of the Southern African Atlas of Agrohydrology and Climatology (Schulze, 1996). The grid, illustrated in Appendix 2.3, was used as input to the zonal statistics procedure, detailed in Section 6.6.4, where the average rainfall seasonality was calculated for each catchment.

#### 6.6.1.4 Simulated average annual recharge

The MAP and rainfall concentration values used above are indicators of the likelihood and timing of recharge which may be experienced by a region. A simulated recharge amount is, however, likely to be more representative. Three different sources of recharge were used for this study.

Vegter (1995) produced a recharge map of South Africa as one of his National Groundwater Maps. He did this by considering a number of criteria and guidelines outlined below:

(a) A comparison of recharge with baseflow in the eastern and southern parts of South Africa yielded a mean difference of approximately 30 $mm.a^{-1}$ for the underestimation of recharge by baseflow. The guidelines which Vegter (1995) followed when relating recharge and baseflow are summarised in Table 3.

(b) In the no baseflow areas the recharge contours were determined using effective rainfall. Effective rainfall is defined as that part of the rainfall which is available for the wetting of the soil and of which a fraction may infiltrate beyond the root zone (Schulze, 1995a). The *ACRU* model was run for each of the 712 relatively homogeneous rainfall response zones (Dent *et al.*, 1990) to determine the effective rainfall for each zone. An estimate of how much of the effective rainfall reaches the groundwater zone was obtained by comparing it with point recharge estimates.

**Table 3 :** Recharge values estimated from baseflow (After Vegter, 1995).

| Mean Baseflow ($mm.a^{-1}$) | Mean Recharge ($mm.a^{-1}$) |
|---|---|
| 0 (edge of area) | 25 |
| 10 | 37.5 |
| 25 | 50 |
| 50 | 75 |
| 100 | 110 |
| 150 | 160 |
| 200 | 200 |

(c) In semi-arid to arid areas with a thick sand cover, like in the Kalahari, there is much debate as to the amount of average annual recharge. Using several guidelines proposed by various researchers Vegter decided to class these areas as having less than 1 $mm.a^{-1}$ recharge. Over much of these areas the effective rainfall is less than 100 $mm.a^{-1}$ and as such recharge is limited to the occasional high rainfall events.

Vegters (1995) recharge coverage was converted to a grid, is illustrated in Appendix 2.4, and was used in the Zonal Statistics procedure, detailed in Section 6.6.4, where the average recharge was calculated for each catchment.

A further recharge grid was obtained from the Southern African Atlas of Agrohydrology and Climatology (Schulze, 1996). The grid was obtained by conducting an *ACRU* simulation for each of the 1947 quaternary catchments using the improved rainfall database established by Meier (1995) for the quaternary catchments. Instead of using the Acocks vegetation data it was assumed that each catchment contained veld in fair condition. The resulting recharge data were used to create a recharge grid, which is illustrated in Appendix 2.5, and was used in the Zonal

Statistics procedure, detailed in Section 6.6.4, where the average recharge was calculated for each catchment. The results obtained from each of these recharge studies are compared and discussed in Section 7.3.3.

### 6.6.2 Geology

Geology will have an effect on the infiltrated rainfall not only in influencing its rate of percolation through the vadose zone to reach the zone of saturation, but also on the ability of the aquifer to store and transmit this water laterally to the stream. The vadose zone is that portion of the geologic profile below the surface of the earth but above the first water bearing aquifer (Cullen *et al.*, 1992) while the aquifer is the consolidated or unconsolidated rock that serves as the water bearing unit (Aller *et al.*, 1987).

The National Groundwater Maps produced by Vegter (1995) have provided a unique and simplified geology map of South Africa in that it is specifically adapted for hydrogeological purposes. Vegter not only considered the age of the various lithostratigraphic units, but the degree of metamorphism to which they have been subjected as well the degree of fracturing and deformation which they commonly exhibit. Vegters hydrogeological map is provided in Appendix 2.6.

A summary of the geology which occurs within each catchment was produced by unioning the DWAFs catchment boundary coverage with the coverage of the hydrogeological map produced by Vegter (1995). The *ARC/INFO* frequency function was then used to output the proportion of each catchment composed of each rock type and lithostratigraphic unit. The results for each catchment are detailed in Appendix 2.7 which contains a detailed key of both the lithostratigraphy, rock types, metamorphism and deformation.

This information was used to develop a geological index. Many researchers have noted that the use of a geological index in baseflow characterisation is not only important but critical if realistic results are to be achieved (Beran and Gustard, 1977; Brown, 1981). This is particularly so when estimating baseflows in a geologically heterogeneous ungaged catchment (Browne, 1981). In order to assess the influence of geology on baseflow a numerical system of describing the hydrogeological properties of each formation must be considered (Wright, 1970). If the effects of geology on baseflow could be expressed numerically then this could be used in baseflow models.

However, many workers have indicated that it is difficult to establish and quantify these effects and hence most studies have only qualitatively shown the relationships between baseflow and geology (Ayers and Ding, 1967; Klaasen and Pilgrim, 1975; Browne, 1981; Demuth and Hagemann, 1994). Ayers and Ding (1967) attribute the failure of researchers to draw quantitative conclusions to the complex interaction of landuse and geological materials which they believe may cause greater variability of the hydrological regime within a region than between such regions. Demuth and Hagemann (1994) believe that the problem is not only due to a lack of extensive large scale maps of hydrogeological and geological parameters but the problem of developing an index which adequately describes the impact of geology on runoff. Wright (1970) states that the development of a geological index will inevitably lead to generalizations.

It has been noted that geological differentiation is on the basis of genesis which is not always very helpful to the hydrologist. A similar problem has been encountered with soils maps (Browne, 1981). A single numerical hydrological expression is difficult to derive in that it has to characterise a number of geological formation constants, namely infiltration which controls the recharge of the geological formation, porosity which controls the volume of water that can be stored and permeability which is a measure of the formations capacity to yield water (Browne, 1981). These properties do not always work in the same direction which complicates matters. Browne (1981) provides a succinct summary of the various ways, including the use of the recession curve, in which these geological effects may be quantified.

#### 6.6.2.1 Previous geological indices

Most studies to date have examined the influence of geology on baseflow by first grouping the basins according to geology. Even fewer of the authors attempted to include geology as a variable in their regression equations.

Cross (1949) plotted area normalised duration curves which show remarkable differences in their lower ends. This is ascribed to the effects of geology on the baseflow. Cross (1949) selected the discharge which is equalled and exceeded 90% of the time as his geohydrological index as at this point the flow is assumed to come almost exclusively from groundwater sources. Wright (1970) used a nomograph to graphically determine the geological indices of several types of formations within the Lothians. Klaasen and Pilgrim (1975) derived three semi-quantitative measures of the geological diversity. Firstly they determined an aquifer rating based on the potential of the surface geologies ability to act as a sources of supply of low flow. The percentage of the stream with alluvial deposits, weighted according to the location of the alluvium relative to the catchment outlet, was the second measure. The third measure is a combination of these first two. Klaasen and Pilgrim (1975) concede that there is a great deal of subjectivity involved in assigning values to these indices. Attempts to relate these geological indices as well as other geomorphological indices to the recession constants proved to be unsuccessful.

Pereira and Keller (1982a) while studying recession in 11 pre-Alp basins used two hydrogeological variables in a stepwise regression analysis to determine the effects of basin characteristics on recession parameters and flow component volumes. The first index was named $G_1$ and calculated from empirical values of estimated bedrock permeabilities while the second index $G_2$ was the result of $G_1^2$. Pereira and Keller (1982a) found that the baseflow recession co-efficient is related to the parameters $G_1$ and $G_2$ such that when the permeability decreases the recession co-efficient increases. Arihood and Glatfelter (1986) defined their recession index as the time required for the discharge to fall one log cycle. Hayes (1991) using a group of generalised rock types determined the percent of the basin underlain by each generalised rock type. The proportion of each rock type was used in the regression analysis.

Kobold and Brilly (1994) indexed geology using the baseflow index and assumed the values summarised in Table 4 for the different types of geology.

**Table 4 :** Summary of the BFI values used by Kobold and Brilly (1994).

| Geology | BFI |
|---|---|
| Alluvium, limestone | 0.85 - 0.95 |
| Sandstone, conglomerate and dolomite | 0.70 - 0.80 |
| sandstone and marl | 0.50 - 0.70 |
| Marl and clay | 0.30 - 0.50 |

Using these classes the index of geology for each catchment was determined using a GIS. Kupczyk *et al.* (1994) used flow duration curves to enable comparisons between the selected rivers. They noted that the similarity of the curves and the difference in their slopes was associated with the geology of the catchments along with the magnitude of the underground feeding. The development of Demuth and Hagemann's (1994) geological index was carried out in several steps. Firstly, hydrogeological data such as daily available water yield, groundwater capacity and groundwater location were obtained from various maps. Using this data fourteen hydrogeological associations were found to be present within the study area. The area occupied by each association was then determined. With the use of the geological map the various hydrogeological associations were linked with the geological formations to define hydrogeological classes. These hydrogeological classes were then regressed against recession coefficients for each catchment. Demuth and Hagemann (1994) state that the close relationship derived between the recession constant and the hydrogeological indices indicates the importance of the recession constant as a measure of catchment response.

It is evident from the literature that several attempts have been made at deriving and using a geological index in baseflow recession research. It is also evident that the various methods have met with varying success and consequently the opinion of Pereira and Keller (1982a) that an improved definition of geological indices would be useful for further research is not surprising.

#### 6.6.2.2 Current geological index

A geological index was required for the current study and hence an index was developed. This geological index was based, in part, on that developed by Klaasen and Pilgrim (1975). Each lithology was assigned a value which describes its potential to produce and maintain baseflows. A value of 50 is assigned to represent a lithology which has a high capacity for baseflow, *eg*. a porous sandstone, while a value of 5 is assigned to represent a lithology which has a poor capacity for baseflow, *eg*. finely crystalline dolerite. Intermediate values between these two limits are assigned depending on the rock types present within the catchment under consideration. These values have little physical meaning in that they cannot be measured and the assignment of a value to a lithology is subjective and dependant on the individual assessing the baseflow potential. These assigned values are then adjusted according to the degree of deformation and metamorphism of the lithology. This is best illustrated with an example.

Vm represents a lithology composed of dolomite, chert, conglomerate, shale and subordinate amounts of quartzite. This lithology was assigned a value of 50 in terms of baseflow potential. This lithology also exhibits low grade metamorphism which has a value of 1 (*cf.* Key to Appendix 2.7) and has been moderately deformed which has a value of 2 (*cf.* Key to Appendix 2.7). It is assumed that deformation introduces secondary pores which increases the baseflow potential while the degree of metamorphism reduces the baseflow potential. The final baseflow potential value is obtained by multiplying the original value, in this case 50, by the deformation value, in this instance 2, and dividing the product by the metamorphism value, which is 1. The final value is the baseflow potential and has a value of 100 for the example. For those catchments which are composed of multiple lithologies this baseflow potential for each lithology is area weighted and a total for the catchment determined.

While this geological index is simplistic in its design it is the simplicity which makes it ideal for use along with the fact that a number of geological factors are considered which adds a degree of realism. These geological indices are summarised in Appendix 2.7.

### 6.6.3 Morphological Variables

Based on the literature review provided in Chapter 4 it was decided that the following morphological variables would be derived for use in this study, *viz*., catchment area, average catchment slope and drainage density.

#### 6.6.3.1 Catchment area

The catchment area was obtained from the List of Hydrological Gauging Stations (LHGS) published by the Department of Water Affairs and Forestry (DWAF, 1990) which provides information regarding the gauging stations, including the latitude, longitude, drainage region, catchment area and the start and end date of streamflow measurement. The catchment area provided in this publication was assumed to be correct. These catchment areas are listed in Appendix 2.8.

#### 6.6.3.2 Average catchment slope

While the UNP DAE have a minute by minute of a degree lattitude/longitude elevation grid of South Africa this was deemed unsuitable for conversion to a slope grid for the determination of average catchment slopes because of the number of relatively small (<40km$^2$) catchments which are under investigation. This would have resulted in a small number of the 1.6 by 1.6 km grid cells being used to derive the average slope in these small catchments, which is statistically undesirable.

As a result a 200m digital elevation model (DEM) of South Africa had to be created as described in Section 6.7.3. This 200m elevation grid was converted into a slope grid using the *SLOPE* grid function in *ARC/INFO* which fits a plane to a cell using its altitude and that of its eight surrounding neighbours. The resulting slope grid was used in the Zonal Statistics procedure, detailed in Section 6.6.4, where the average slope was calculated for each catchment.

#### 6.6.3.3 Drainage density

Drainage density is expressed as the ratio of the total length of all stream channels within the catchment to the total area of the catchment (Whittow, 1984). The total length of stream channels within each catchment was defined using the Water Research Commission's national rivers coverage established during the Surface Water Resources 1990 survey (Midgley *et al.*, 1994). This was achieved using *ARC/INFO* where the catchment boundaries were used to clip out those rivers which fall within each catchment. The attributes of the arcs which define these rivers, including length, were unloaded to an ASCII file and summed using a spreadsheet package. The drainage densities for each catchment were calculated with this total length of streams and the area which was obtained from the LHGS (DWAF, 1990), as described in Section 6.6.3.1. These drainage density results are given in Appendix 2.9.

### 6.6.4 Zonal Statistics using *ARC/INFO*

In order to determine the average grid cell value within each catchment the *ARC/INFO ZONALSTATS* command was employed. This requires a digitised polygon coverage of the catchment boundaries for each of the catchments under consideration. The coverage of the catchment boundaries was supplied by the GIS section of the DWAF (*cf.* Section 6.7.1). This coverage was then converted to a grid using an implicit *ARC/INFO* command to produce the first input grid for the *ZONALSTATS* command, from which means are to be calculated. The mean of the grid cells which fall within the catchment boundaries is calculated. The results from this process are detailed in Appendix 2.9.

## 6.7 DEVELOPMENT OF USABLE DATA SETS

Extensive use has been made of data during the course of this study with much of it being obtained from various para-statal and state institutions. As with most data sets there are problems associated with them. The problems encountered and the methods by which these data problems were solved are described below.

### 6.7.1 The DWAF GIS Catchment Boundary Coverage

This GIS coverage contained all of the catchment boundaries for catchments ranging in size from the Primary drainage regions down to the Quaternary catchments and even down to those for individual gauging weirs. The catchment boundaries for the gauging weirs under investigation were selected from this data set. Problems included different gauging weir naming conventions to those given in the LHGS (DWAF, 1990), the absence of certain catchment boundaries and inconsistent catchment sizes.

The LHGS utilises a six digit alphanumeric gauging weir name, *eg.* C2H018. The first digit refers to the primary drainage region (C) and the second to the sub-drainage region (2) in which the gauging station is located. The third digit refers to the type of gauging station (H for flowing water) and the last three digits are a serial number (018) identifying the gauging station within the sub-drainage region under consideration (DWAF, 1990). The DWAF GIS section had modified the gauging weir name to a seven digit alphanumeric system, *eg.* C21H018. The first two and last four digits were consistent with that discussed above and assigned by the LHGS. The third digit was included by the DWAF GIS section to distinguish between the different levels of catchments, *eg.* between primary and quaternary catchments. Telephonic communications with the DWAF GIS section resolved the confusion caused as a result of this difference in naming conventions.

The exact number of catchment boundaries which are not present in this DWAF coverage is uncertain. Of the catchment boundaries required for this study, three were not present and resulted in these gauging stations having to be eliminated from the study.

Using the coverage and *ARC/INFO* the catchment sizes of the catchments under consideration were calculated. The catchment area provided in the DWAF's LHGS was compared with that calculated using the GIS and the catchment boundaries obtained from the DWAF. The results of the comparison indicated that there was a problem with the supplied coverage as in more than 40% of cases the size difference was beyond 10%. In all of these cases it was noted that the calculated catchment size was smaller than that listed in the LHGS. This fact fostered the suspicion that catchment nesting was the cause of the problem. Investigation confirmed that this

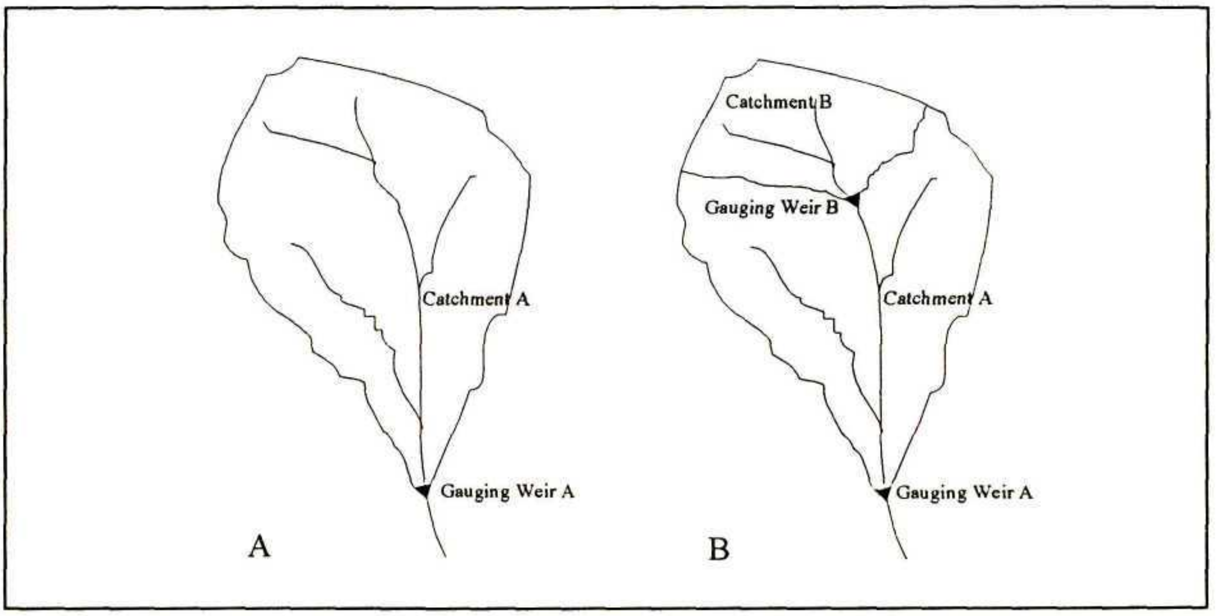


**Figure 15**: Illustration of the nesting problem encountered in the DWAF catchment boundary coverage

was indeed the problem and was a function of the digitisation process. The GIS catchment boundaries defining a catchment do not include those upstream catchments discharging into the catchment under consideration. Figure 15(B) illustrates this nesting problem, where Catchment A should have a calculated catchment area of say 470 km$^2$ as in Figure 15(A), but is reported as having a catchment area of say 390 km$^2$ due to the presence of catchment B upstream. Arc editing to create new catchment boundaries to represent the many undersized catchments resolved this problem. The catchment area differences between the altered GIS coverage and that provided in the LHGS, expressed as a percentage , are summarised in the frequency chart in Figure 16. The four stations which exhibit a difference in catchment size of greater than 10% are, except for a single case, small catchments where the absolute differences are still quite small. The exception is for station number H7H001, where an error of over 4000km$^2$ in catchment size resulted in this stations being eliminated from the study, as the problem remained unresolved.

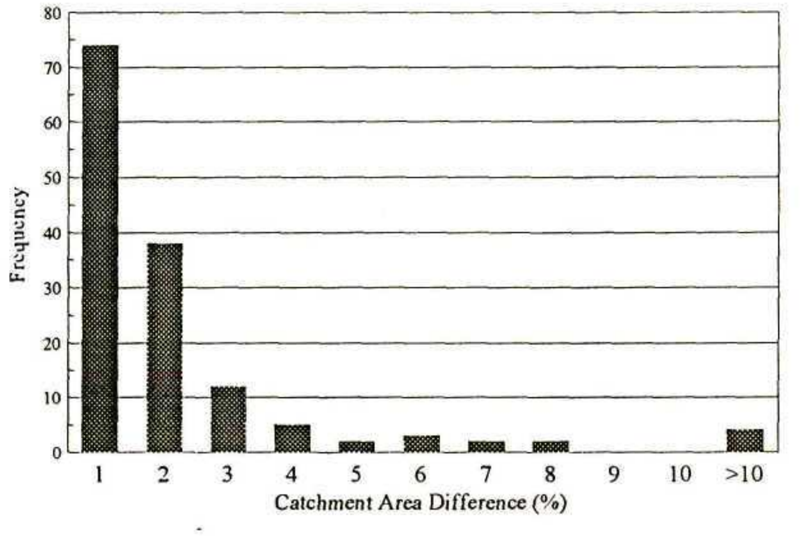


**Figure 16**: Frequency chart of the catchment area difference between that listed by the DWAF in the LHGS and that calculated from the GIS coverage

### 6.7.3 The 200 m National Digital Elevation Model

Prompted by the need for an elevation grid at a resolution finer than one minute by one minute of a degree lattitude/longitude, the 200 m National Digital Elevation Model (NDEM) of South Africa was purchased from the Chief Directorate of Land Surveys and Information. A description of the NDEM and the manner in which the DLSI data were converted into an *ARC/INFO* GIS elevation grid are provided below.

#### 6.7.3.1 Description of the NDEM

The NDEM was determined from 1:150 000 scale aerial photographs. The resultant data were converted into raster form with each grid point representing the centre of a cell. The NDEM is at a 200 m resolution in areas which exhibit relief, like the Natal Drakensberg, while in flatter areas, like the Karoo, it is at a 400 m resolution (DLSI, 1996). The data are not available as a single data file and were requested in degree blocks.

The purchased data were supplied in 77 complete degree blocks, 153 quarter of a degree blocks and 143 one sixteenth of a degree blocks. The unit of the planimetric co-ordinates is the metre.

The co-ordinates are based on the Gauss Conform Projection (Clarke 1880 modified spheroid) with the central meridian of each zone being comparable to the South African Co-ordinate System (DLSI, 1996). The NDEM therefore consists of a number of sub-databases, each being 2 degrees (±220 km) wide. The data were supplied in 9 sub-directories which correspond to the 9 central meridians which cover South Africa, namely, 17, 19, 21, 23, 25, 27, 29, 31 and 33° E of Greenwich.

Initial problems included data supply, compatibility and format. The data could only be supplied on 4 mm DAT tape or Compact Disk (CD) and could not be *FTP'D* to or from an anonymous *FTP* site. This not only provided unnecessary delays, but also various logistical problems. The data supplied on CD were in ASCII and could not be down loaded onto the Computing Centre for Water Research's (CCWR) Unix system using their CD-rom drive. Consequently, the data had to be *FTP'D* to the CCWR from a remote terminal.

The data are supplied in a format consistent with the National Standard for the Exchange of Digital Geo-Referenced Information (CCNLIS, 1990), commonly referred to as the National Exchange Standard (NES) format. This format has many problems inherent in its structure. The first is that similar data in each file are not consistently stored in the same file positions. Instead, use of record and file separators is made to distinguish the data from one another. While this may conserve disk space it is, however, a convention reminiscent of the past, is seldom used today and complicates the ease of use of the data.

The second problem concerned the NES convention for the storage of gridded altitude data where the data are stored in the form of a matrix with a "saw tooth" ordering of the elements. This in effect starts at the South-West corner of the area under consideration and elevations are given sequentially along a profile moving in a northerly direction. Successive northerly profiles are added in an easterly direction to compose the area under consideration. Each data file thus contains the co-ordinates of the four corners of the area along with the sequential elevation data and the grid size (200 or 400 m) used (DLSI, 1996). Converting this data into a format which may be readily imported into a GIS like *ARC/INFO* is problematic and requires a sophisticated computer program. Fortunately for this author such a *PERL* program had been written by a colleague (Kiker, 1996) who had used this program to create a DEM for use in the Kruger

National Park (KNP). Kiker(1996) had also developed a technique for manipulating these imported files within *ARC/INFO* to generate elevation grids and link these together.

#### 6.7.3.2 Description of the *ARC/INFO* NDEM generation process

The size of the DEM to be created in this study was substantially larger than that for the KNP and hence a suite of *Fortran 90* and script programs had to written to automate the process of converting the data into *ARC/INFO* import files and generating the elevation grids within *ARC/INFO* for each of the sub-directories. The process undertaken to achieve this is outlined below:

(a) The name and grid size of the file to be processed is determined, *eg.* 2630a.*dat* 200 m.

(b) Kikers (1996) *PERL* program is used to convert the *.dat* file into two import files named *.aat* and *.gen*, *eg.* 2630a.*aat* and 2630a.*gen*. The file with the .aat extension consists of a record number representing each grid cell and its altitude value while the *.gen* extension file contains a corresponding record number along with the latitude and longitude of the centre of each grid cell.

(c) After entering *ARC/INFO* a points coverage is generated using the *.gen* file as input.

(d) Using *ARC/INFO* tables the *.aat* file is added to a template to create an attribute table in addition to the point coverage attribute table.

(e) The point coverage attribute table is then combined with the additional attribute table to create a comprehensive attribute table.

(f) The point coverage is thereafter converted to a grid coverage.

(g) If the grid size was 400 m then the grid was resampled to a 200 m grid using the *Nearest Neighbour* interpolation technique. While the *Cubic Spline* technique of interpolation is recommended in the *ARC/INFO* manual for the resampling of continuous type data, such as elevation, it has the disadvantage of altering the original values during the interpolation process (ESRI, 1990). Hence it was decided that assignment using the value of the *Nearest Neighbour*, which is more suited to categorical types of data like land use, would be utilised, as it does not alter the original values despite the fact that the grid which it produces is geographically not as smooth as that produced by the *Cubic Spline* technique. Considering that the 400 m grids were produced in areas where the terrain was relatively flat it was deemed that this technique would be the more suitable for resampling.

(h) Once all of the grids within each sub-directory have been generated and resampled (if they were 400 m in resolution) they are joined together using the *ARC/INFO MERGE* command. The *MERGE* command overlays the grids joining them and where they overlap the first no data value is taken as the correct value. The convention adopted during the *MERGE* process is as follows: The starting grid was the most North-Westerly grid. Successive grids were merged in an easterly direction to create a profile. Successive profiles were then joined in a southerly direction.

(i) The final grid is a two degree wide elevation grid for the central meridian under consideration. Errors in the process were assessed visually in the final grid by checking that no abrupt changes in topography occurred.

Error checking showed that two types of errors were present in certain of the grids. The first error, which was present in three of the two degree wide grids, was that five of the grids supplied plotted in an incorrect location. Investigation revealed that these data files were in an incorrect projection for the sub-directory, *eg*. files 2432cc.*dat*, 2532aa.*dat* and 2532ac.*dat* which are in the 33 °E of Greenwich sub-directory and should be in 33° projection are in actual fact in 31° projection. Consequently all files were checked to ensure that their projections were correct. Those files which were incorrect were re-projected to the correct central meridian. The second type of error is that of incorrect data and was detected in a single case, *viz*. file 2425dd.*dat*. The data consist of alternating zeros and what appear to be the correct values. The error was reported to the Directorate of Land Surveys and Information and a correct data file was received.

(j) Once each of the two degree wide grids for each of the central meridians were complete they were re-projected from the Gauss Conform Projection to Geographic Projection. The Geographic Projection does not utilise central meridians. Thus, once each of these two degree wide grids had been re-projected, they were joined starting in the west and proceeding to the east. The product was a 200 m elevation grid of the entire country.

(k) Verification of the grid values was difficult to undertake as another grid is required against which to compare the currently formed grid. The data for the other grid should also have been collected by another technique, *eg.* satellite imagery. An 800 m resolution elevation grid of Africa is obtainable from the United States Geological Survey (USGS) (Gesch, 1996). This 800m grid was down loaded from the USA (Lynch, 1996) and used in a comparative study. The results are presented in Section 7.2.4, where it is concluded that the grid generated from the data purchased from the DLSI must be accepted as being the best possible DEM of South Africa, despite any imperfections.

(l) The national 200m grid has a further imperfection in that it does not include any altitude data for Lesotho which has implications for the Orange River and other catchments. Hence it was decided to clip out those data which are missing from the 200 m grid from the 800 m grid down loaded from the USA. These data were resampled to 200 m using the *Nearest Neighbour* interpolation technique and merged with the NDEM.

(m) Analysis of the NDEM to determine if it contains sinks was undertaken using the *ARC/INFO SINK* command. A sink is defined as a cell or spatially linked set of cells whose flow direction can't be assigned one of the eight valid values in a flow direction grid. This occurs when surrounding cells are at a higher elevation or two cells flow into each other to create a two cell loop (ESRI, 1990). These sinks typically result from sampling and rounding errors. The maximum depth of these sinks was determined using the following technique (ESRI, 1990):

  (i) Using the *WATERSHED* function the contributing area for each of the sinks was calculated;

(ii) Using the *ZONALMIN* function a grid of the minimum elevation in each of the sink watersheds is calculated;

(iii) Using the *ZONALMAX* function a grid of the maximum elevation in each of the sink watersheds is calculated;

(iv) Subtraction of the two grids provides the maximum sink depth.

This sink depth value is an important input in the *FILL* function described below as the deepest sink value for the NDEM is required. These sinks were removed by using the *FILL* command in *ARC/INFO*. This fills the sinks by imagining that the sink is filled with water until just before it overflows. This is an iterative process as the filling of a sink often creates a further sink. The process is thus conducted until all sinks are removed. This filled national 200m DEM was the input data set for any work which was conducted using an elevation grid during the course of this study.

# 7. RESULTS

The results obtained during the course of the study are detailed in this Chapter, along with substantiating discourse where necessary. Results pertaining to aspects of the study other than the MRCs are dealt with first in Sections 7.1 and 7.2, while those relating to the MRCs follow in Sections 7.3 to 7.6.

## 7.1 COMPARISON OF THE 200 m NDEM AND THE 800 m USGS DEM

The filled 200 m NDEM was compared with the 800 m USGS DEM by resampling the 800 m USGS grid to a 200 m resolution and then filling the grid using the same technique as that described for the NDEM (*cf.* Section 6.7.3). In order to ensure that the effects of the resampling technique were accounted for the 800 m USGS grid was resampled using both the *Nearest Neighbour* and the *Cubic Spline* techniques. The absolute differences between the NDEM and the resampled USGS DEM are summarised in the histograms provided in Figure 17 from which it will be noted that the differences in elevation between the two grids are generally below 20 m in magnitude.

This leads one to suggest that the 800 m USGS DEM resampled to a 200 m resolution is of a similar quality to the 200m NDEM supplied by the Directorate of Land Surveys and Information. This simple comparison is, however, far from exhaustive and further comparisons are to be undertaken. Owing to the amount of time invested in the 200 m NDEM and the associated error checking that has been undertaken on the data set, both by the DLSI and during the current study, the NDEM was selected as being more representative and was therefore used during the course of this research.

## 7.2 ELIMINATION OF CATCHMENTS FROM THE STUDY.

Once each of the catchments flagged as having a non-homogeneous streamflow record had been removed from the data set which had been obtained from Joubert (1995), 201 catchments remained. A further catchment from the UNP DAE's Cedara research catchment was added to the data set.

Of the 202 catchments the following were eliminated from the study for the reasons given:

(a) One catchment was eliminated due to the lack of a suitable driver rainfall station, which is critical for selection of acceptable recessions.

(b) Three catchments were omitted because the DWAF catchment boundary GIS coverage did not contain their catchment boundaries.

(c) One further catchment was left out as the DWAF catchment boundary GIS coverage contained an incorrect catchment boundary and the problem could neither be reconciled nor corrected.

(d) All four of the catchments in drainage region D had to be eliminated as many of the GIS coverages and grids do not contain any information for Lesotho and all of these catchments incorporate large sections of Lesotho in the upper reaches of their catchments.

(e) A further 59 catchments did not qualify as insufficient recessions could be extracted from their streamflow record in order to define a MRC.

The remaining 134 catchments were used in the analysis of the MRCs and their comparison with the catchment characteristics (*cf.* Section 7.5).

## 7.3 REPRESENTATIVENESS OF THE CATCHMENTS AND THEIR CHARACTERISTICS

In order to derive meaningful results which may be regionalised and readily applied, the catchments selected for the study were required to be representative in terms of a number of criteria ranging from catchment size to rainfall region. Grant (1971) stated that catchment representativeness does not mean that a catchment exhibit the average flow characteristics of a region or that it be of average slope, area and so forth. Rather, it should be representative in that the baseflow characteristics of a catchment with similar characteristics and geology can be determined. This degree of catchment representativeness is difficult to assess and became strained as further stations were eliminated from the study for various reasons (*cf.* Section 7.2).

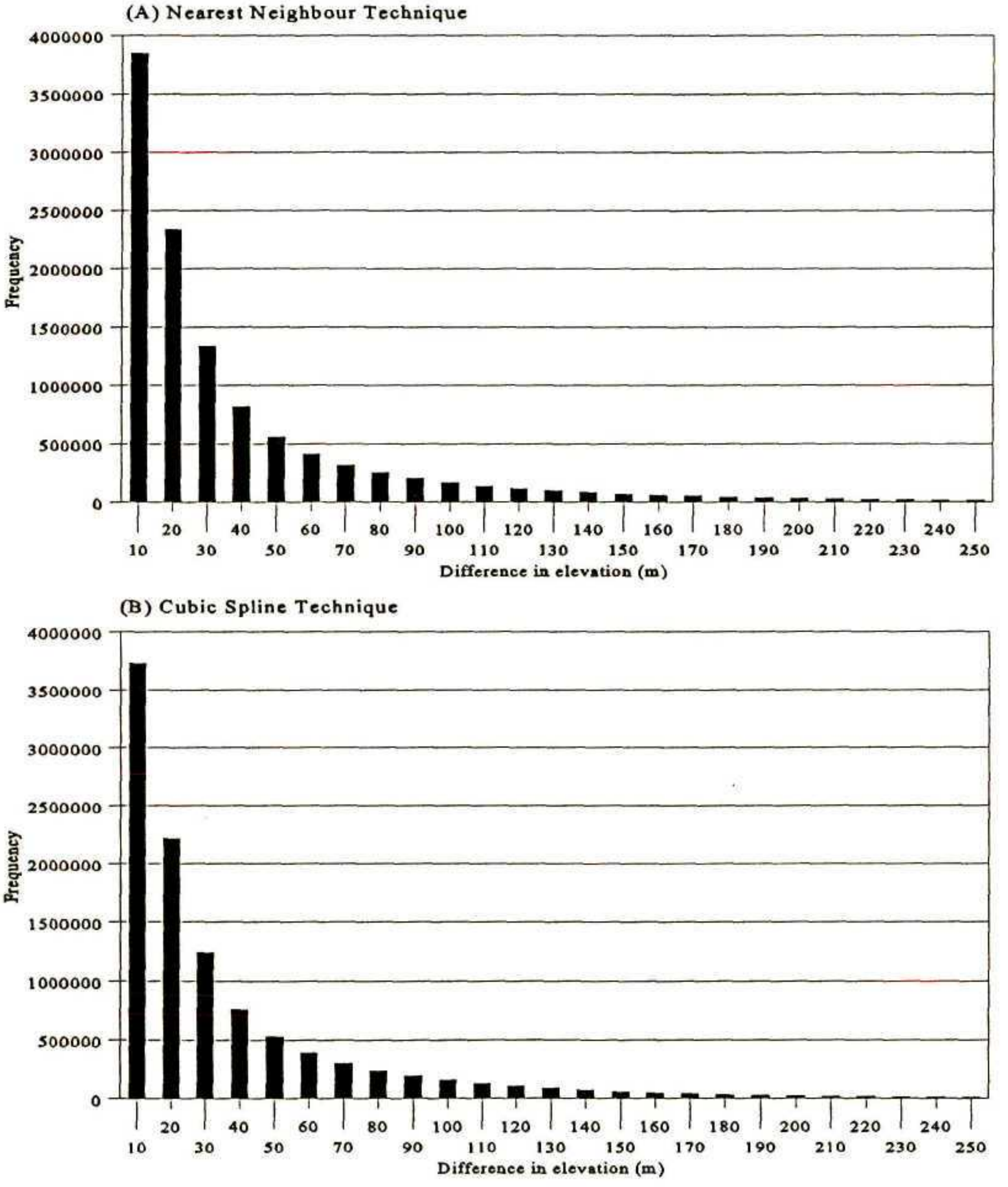


**Figure 17**: Histograms illustrating the differences in elevation between the NDEM and the USGS DEM resampled using (A) the *Nearest Neighbour* and (B) the *Cubic Spline* techniques

### 7.3.1 Spatial Distribution

Figure 18 illustrates the spatial distribution of the 134 catchments throughout South Africa. It will be noted that these catchments not only cover a substantial portion of the region but are well distributed across the region and while they do not occur within every primary drainage region the vast majority of the primary drainage regions are represented. Table 5 summarises the number of catchments occurring within each of the primary drainage regions.

Drainage regions F, M and N are small drainage regions and have a limited number of DWAF gauging weirs within their bounds. Consequently, the non-occurrence of catchments within these regions was not viewed as problematic. While the number of catchments within certain of the drainage regions appear to be insufficient for the development of regionalised trends this of course assumes that regionalisation is to be in terms of these primary drainage regions (*cf.* Section 7.5.1).

**Table 5 :** Summary of catchment occurrence per drainage region.

| Drainage Region | No. of Catchments | Drainage Region | No. of catchments |
|---|---|---|---|
| A | 10 | M | 0 |
| B | 12 | N | 0 |
| C | 6 | P | 1 |
| D | 4 | Q | 2 |
| E | 2 | R | 8 |
| F | 0 | S | 2 |
| G | 9 | T | 9 |
| H | 13 | U | 10 |
| J | 5 | V | 18 |
| K | 9 | W | 4 |
| L | 2 | X | 18 |

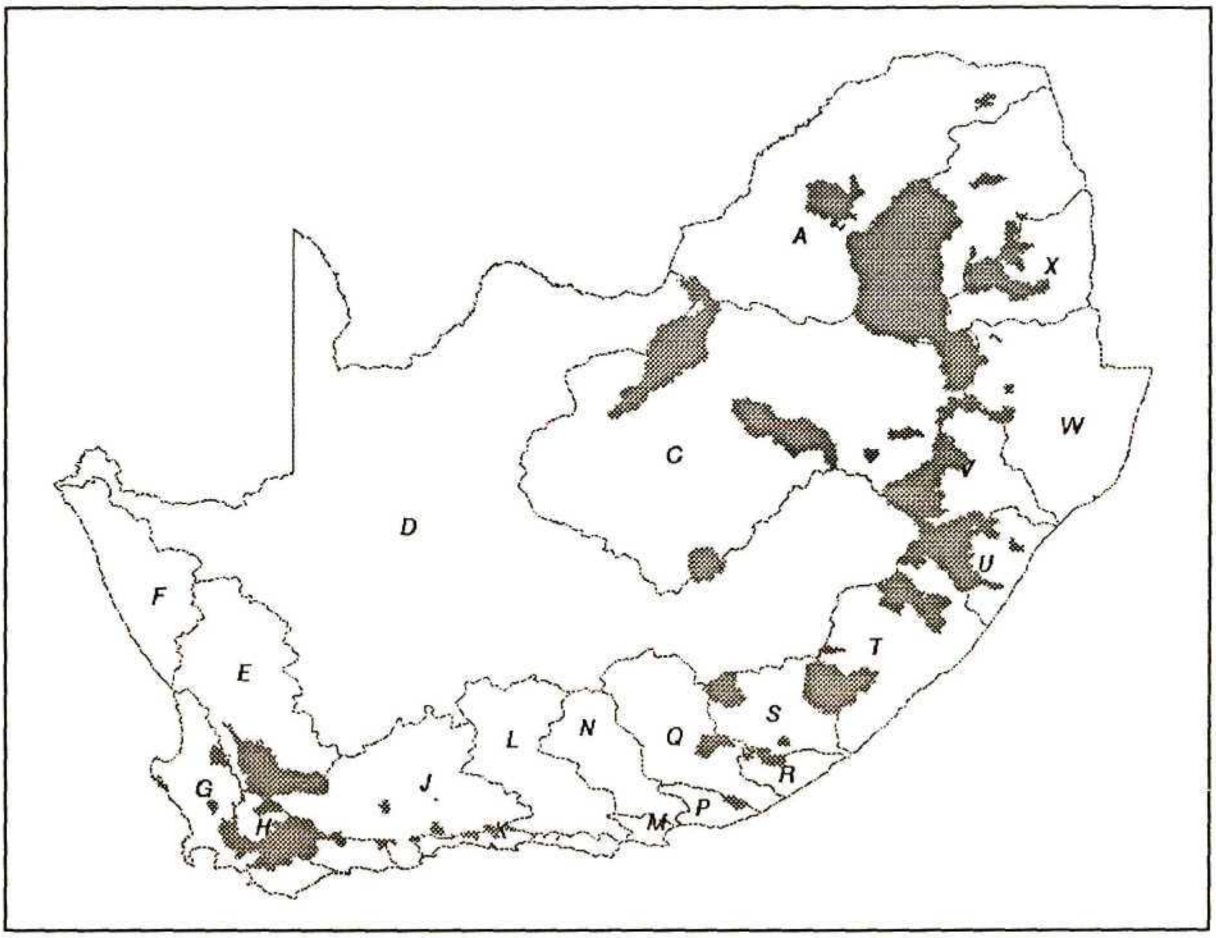


**Figure 18**: Spatial distribution of the 134 selected catchments across South Africa in relation to the primary drainage regions

### 7.3.2 Climatological Variables

MAP and rainfall concentration have previously been identified as the climatological variables which are to be used in the baseflow analysis. These variables describe the likelihood of groundwater recharge and hence the generation and availability of baseflow.

The MAP of the catchments under consideration is well distributed, ranging from 312 mm up to 2313 mm. The rainfall concentration also covers a broad range of values from 3% up to 64%. These distributions are illustrated in a histogram in Figure 19. Both of these variables were considered in conjunction with the catchments' rainfall seasonality classification, which describes each catchment as being either a predominantly early, mid, late or very late summer, winter or all year round rainfall region.

### 7.3.3 Groundwater Recharge

While the climatic variables described in Section 7.3.2 may provide an indirect measure of the likelihood of recharge and hence the availability of baseflow, a more direct measure of the groundwater recharge is likely to be more representative. Two sources of groundwater recharge estimates were obtained for each of the catchments (*cf.* Section 6.6.1.3). The recharge results are detailed in Appendix 2.9.

The *ACRU* simulation recharge values range from 0 mm up to 344 mm while Vegter's recharge estimates range from 17 mm to 180 mm. Both sets of data are illustrated in Figure 20. It will be noted from the results in Appendix 2.9 that the differences between the two recharge studies are relatively small (<10%) in certain instances, but in others the differences are large (>100%). However, a direct comparison between the two is difficult as the *ACRU* simulation reflects net recharge, which is defined as that water which leaves the base of the sub-soil and enters the intermediate zone, while that of Vegter's is that portion which actually accretes to the groundwater store.

These disparities between the recharge estimates indicate the difficulty in approximating the groundwater recharge within a catchment. They also pose a problem in that it is difficult to assess the importance of such broad scale recharge estimates and even more difficult to decide which estimate to use for this study.

### 7.3.4 Morphological Variables

The catchments under investigation reflect a wide range in catchment size from 15 $km^2$ up to 31 416 $km^2$, with an abundance of small (<200 $km^2$) catchments. This skewed catchment size distribution is illustrated in Figure 21.

Average catchment slopes, given in degrees, range in value from less than 0.6 up to 29°. While there is a good spread of average catchment slope values there appears to be a predominance of lower slopes. The skewed distribution of average catchment slopes is illustrated in Figure 21.

The drainage density values, expressed in km per $km^2$, appear to reflect a wide range of values from 0.002 to 29. The distribution of the drainage density values, as illustrated in Figure 21, is skewed towards the lower values.

Despite the predominance of lower values describing the morphological variables, the values do reflect a wide range of possible catchment characteristics. As a result it is concluded that the catchments selected for this study may be considered representative of the diverse morphology found in South Africa.

### 7.3.5 Geology

The spatial distribution of the catchments across the country along with the size distribution of the catchments have implications for the results of the geological investigation such that a number of different lithologies which exhibit varying degrees of metamorphism and deformation are encountered. The geological composition of each catchment is summarised in Appendix 2.7, in which it will be noted that the lithologies range from glacially deposited tillite to the basaltic lavas associated with the Drakensberg. Owing to the sizes of the catchments, a relatively small number of them are composed of a single lithology. While this adds to the complexity of the investigation, it was hoped that this diversity would still be accounted for when the baseflow trends defined by the MRCs were explained.

## 7.4 ANALYSIS OF THE MRCs

Analysis of the MRCs involved the visual inspection of the MRCs in order to establish trends. Determining whether these trends display a regular pattern which may be explained by a simple set of causative factors provides information which may be utilised if a rule based model is to be established.

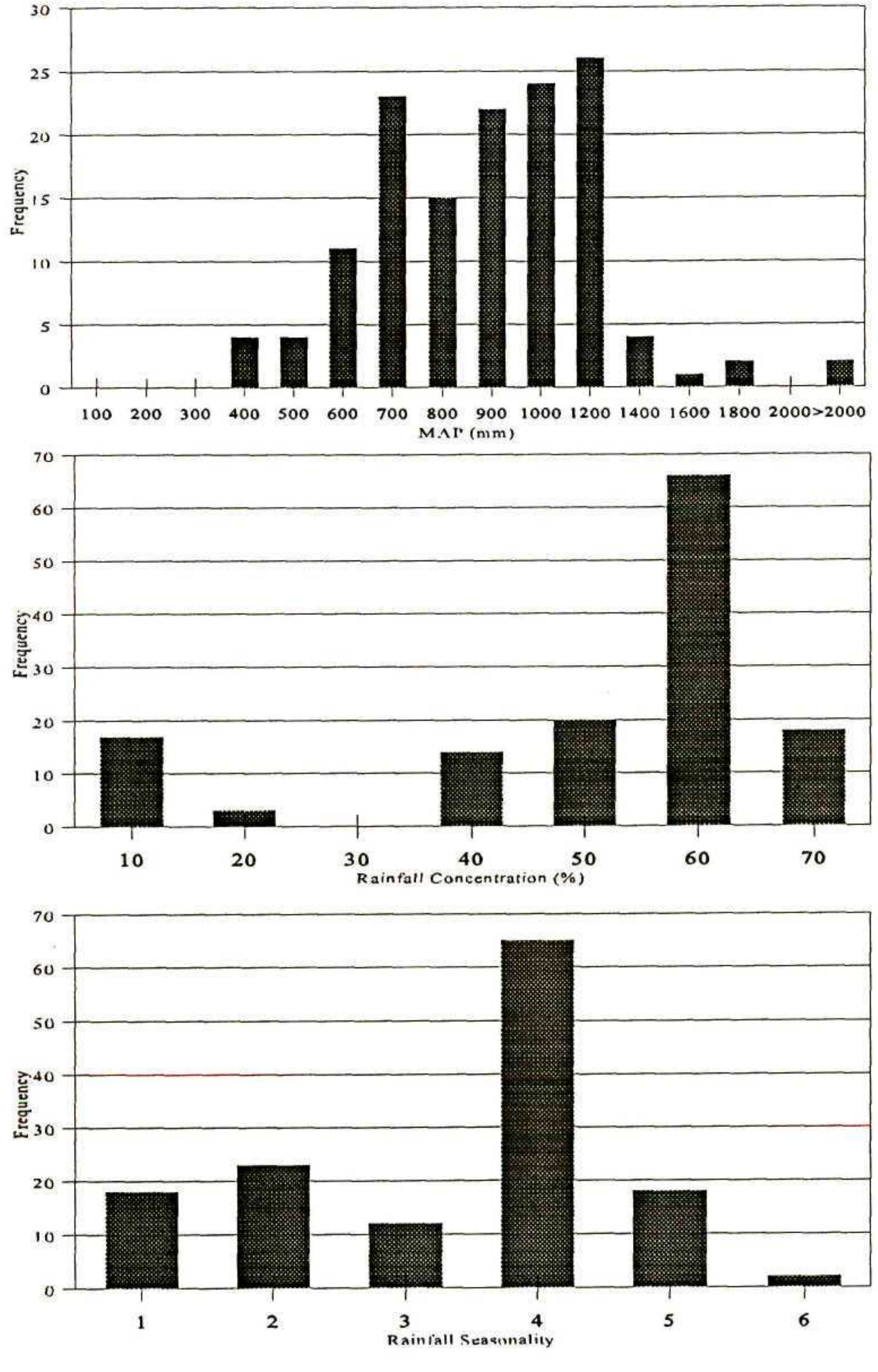


**Figure 19**: Histograms illustrating the distribution of the catchments with respect to MAP, rainfall concentration and rainfall seasonality

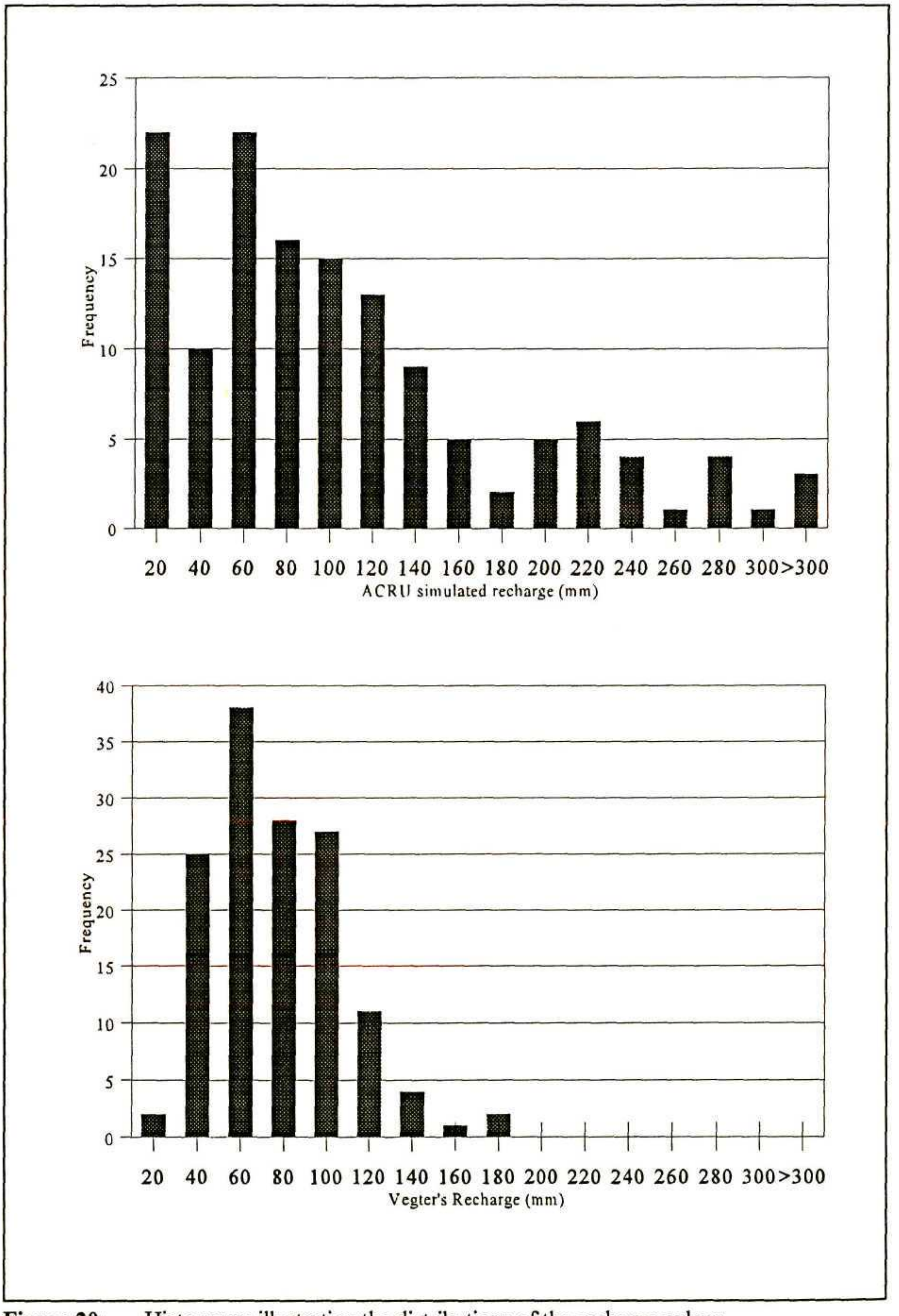


**Figure 20**: Histograms illustrating the distributions of the recharge values

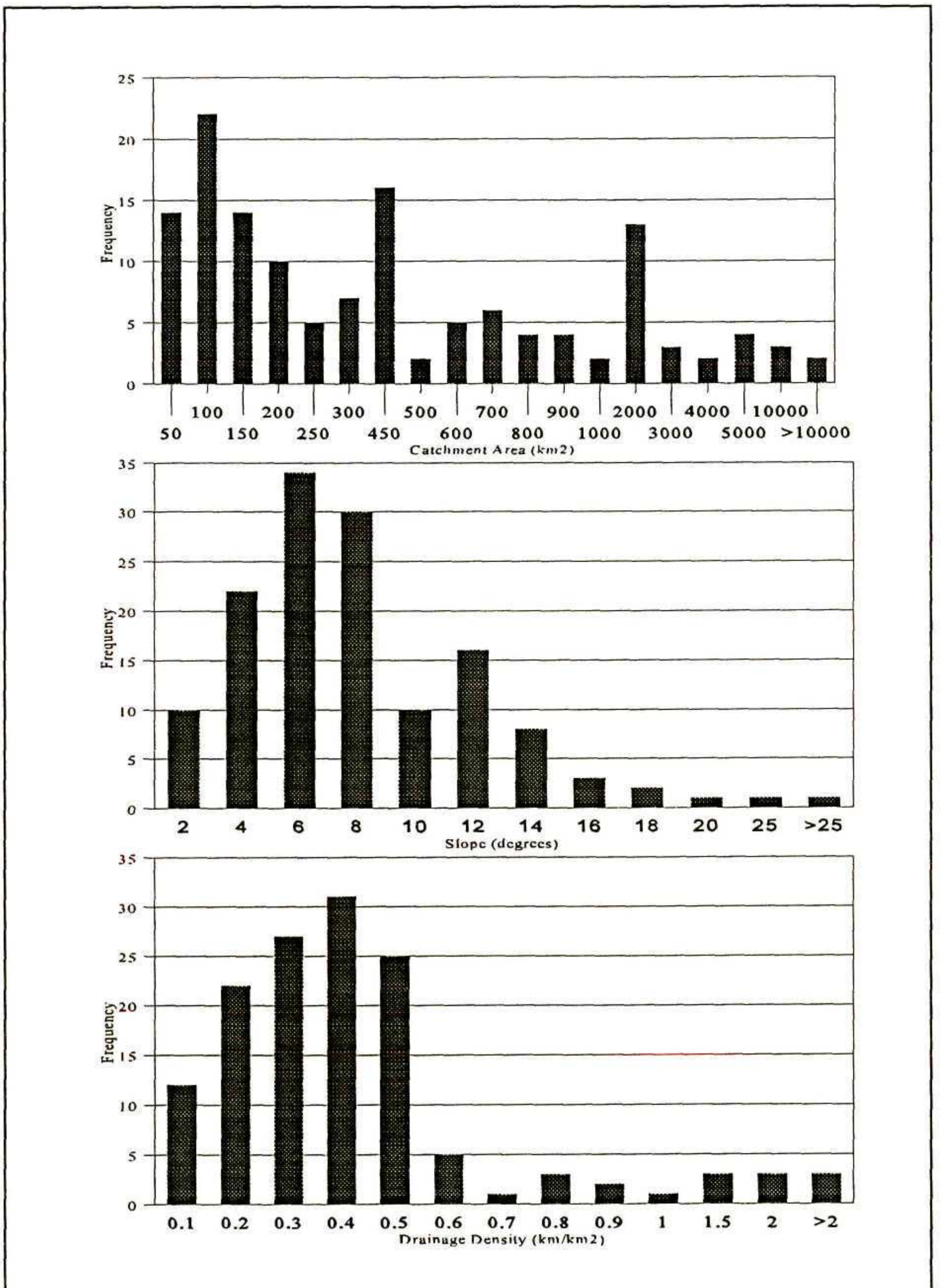


**Figure 21**: Histograms illustrating the catchment area, average catchment slope and drainage density distributions for the catchments

### 7.4.1 Catchments which do not Produce MRCs

Of the 202 gauging weirs 131 produce a MRC for the dry season and 133 produce wet season MRCs. There are 119 gauging weirs in common between the wet and dry season MRCs. These results are summarised in Appendix 2.10. Spatial analysis of the catchments which failed to produce MRCs indicated little. There was a suggestion that catchments which did not produce a dry season MRC occurred in the drier reaches of the country. This hypothesis was further supported by the MAP and rainfall concentration values of many of the catchments. This did not, however, explain many of the catchments' failure to produce MRCs.

A primary factor relating to the failure of catchments to produce a MRC is believed to be the catchment size. The size of the catchment is an indicator of the likely input of water into the catchment as well as its storage capacity. Smaller catchments generally respond to rainfall in terms of hours and not days and as such are likely to be biased by the recession selection criteria as they are less likely to produce recessions of the required duration (*cf.* Section 5.3). Smaller catchments are also likely to produce baseflows which are small in magnitude. These baseflows are difficult to measure accurately owing to limited instrument precision under low flow conditions, and hence the streamflow record is likely to exhibit a great deal of variation. The smaller magnitude of flow also implies that perturbations or losses are likely to have a greater relative effect on the streamflow and this may also result in variation. This variation results in a greater number of apparent streamflow rises and recessions. This affects the duration of the baseflow recessions such that they are less likely to conform to the recession selection criteria (*cf.* Section 5.3). Figure 22 is a histogram of the catchment sizes of those catchments which failed to produce MRCs where it will be noted that there is a predominance of small catchments within this sample.

In the higher rainfall areas the catchment size effect is possibly coupled with the number of rain days in a year. Frequent rainfall events are likely to distort the baseflow recessions or cut them short and in this manner reduce the number of recessions which conform to the recession selection criteria.

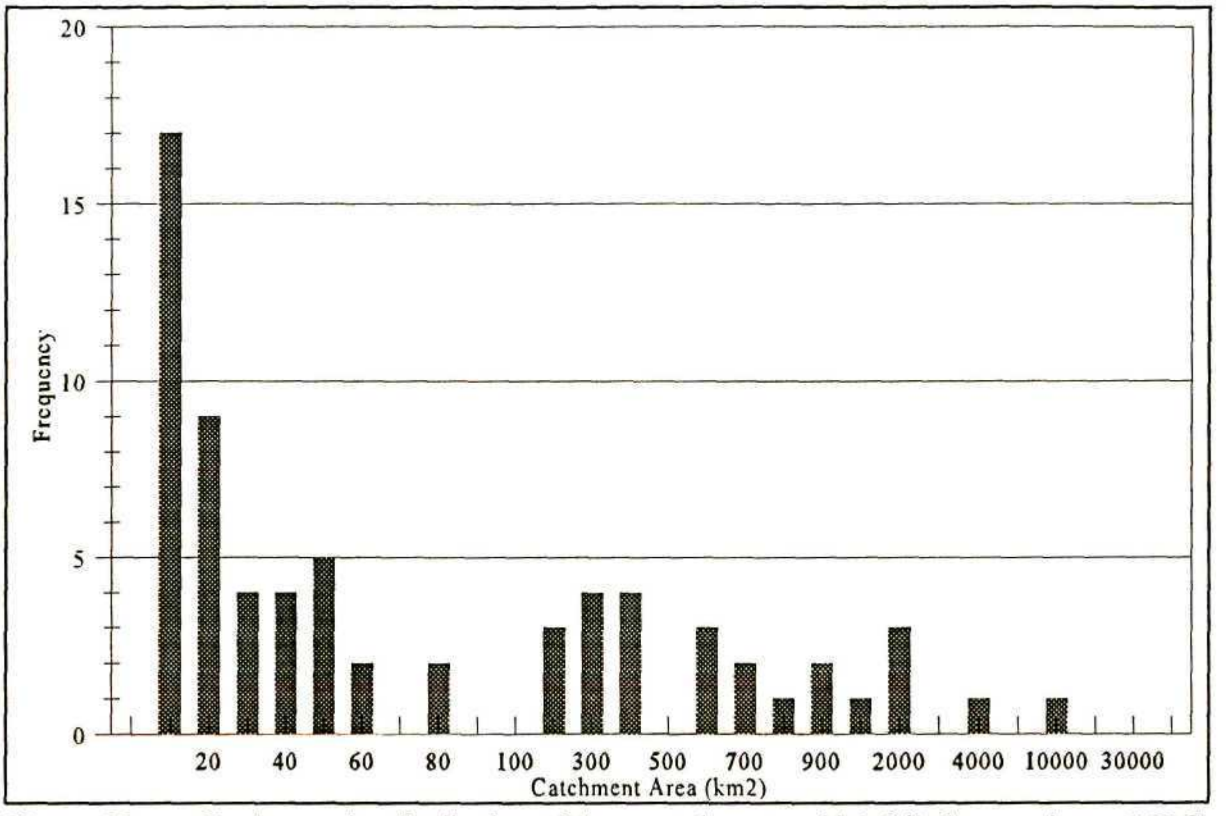


**Figure 22**: Catchment size distribution of those catchments which failed to produce a MRC.

### 7.4.2 Analysis of the Recession Shapes

Having defined multiple segment MRCs for each of the catchments the shape of the MRCs may be evaluated. A semi-log plot of discharge versus time should produce a straight line if the baseflow recedes exponentially. Visual inspection of the semi-log MRCs in Appendix 3.3 provides insight on the exponential nature of these curves.

The MRCs for drainage region A not only appear to recede exponentially, but also at a similar rate. Results of this nature appear to hold much promise for modelling. However, the MRCs for drainage regions B, C, E and G provide a realistic view of the complexities of nature. It will be noted that a large number of the MRCs are curvilinear in shape, which indicates clearly that exponential recession models should be applied with caution in South Africa, as they are not truely applicable. From a modelling perspective it would be of benefit if the different MRCs could be grouped into meaningful groups based on their shape (*cf.* Section 7.5.2).

### 7.4.3 Comparison of the Wet and Dry Season MRCs

In almost all of the catchments the dry season MRC exhibits a shallower slope than the wet season MRC. This trend is expected and attributed to the high ET losses experienced during the wet season which in the summer rainfall regions corresponds with the growing season. Examples of these trends are provided in Figure 23. It will be noted that the recession curves from both seasons exhibit similar, and in some cases even identical shapes. This indicates that the shapes of the MRCs for the different seasons are controlled by a similar set of catchment characteristics, likely to be the geology and morphology of the catchment.

There were, however, a number of exceptions where the wet season MRC exhibited a shallower recession than the dry season MRC (*cf.* Appendix 3.1). Most of these catchments fall within the winter rainfall region. This indicates that the grouping of winter and summer rainfall region wet seasons together as proposed earlier (*cf.* Section 6.4) is inherently flawed. The division of the recessions into seasons was primarily to account for the ET effects. However, despite the fact that winter rainfall regions receive the bulk of their rainfall in the winter, the ET losses are still dominant in the summer. Hence the appropriateness of the wet and dry season classification is questioned and the MRCs were therefore returned to the winter and summer groupings, as before.

Appendix 3.1 also summarises the few non-winter rainfall region catchments where the wet season exhibited a shallower MRC than the dry season. The reasons for this reversal of the wet and dry season MRCs are unknown. Anthropogenic influences are suspected. Having established that the dry season MRCs are likely to be more representative of the potential streamflow (cf. Section 3.4.1) the following results are for the dry season MRCs only.

### 7.4.4 The Effects of Catchment Characteristics on the Half Life of the MRCs.

A physically meaningful descriptor of the rate of recession which makes no assumptions regarding the shape of the recession is the half life (*cf.* Section 4.5.5). The half lives for each of the catchments were calculated from the MRCs and used to determine which of the catchment characteristics affect baseflow. The plots of each of the climatic and catchment characteristics versus the half lives are provided in Appendix 3.2. The scatter and lack of a trend within these plots makes it difficult to evaluate the effects which these various factors have on baseflow. Investigation of the catchments which consistently produce outliers within the data suggested that rainfall seasonality was, in part, responsible for the patterns or lack thereof. Disaggregation of these scatter plots per rainfall region was undertaken. The resulting plots for each of the catchment characteristics look remarkably similar and hence only that for the MAP is provided as an example in Figure 24. It will be noted that the majority of the trend exhibited in Figure 24 (A) is provided by the early (Figure 24 D) and mid-summer (Figure 24 E) rainfall regions.

### 7.4.5 Initial Discharge and Recession Duration

Two further features of the MRCs produced which are noteworthy of discussion are the initial discharge ($Q_0$) and the duration of the MRCs. It would be expected that the larger catchments produce a higher initial discharge than the smaller catchments. A scatter plot of catchment area against the $Q_0$ reveals little and attempts to fit a successful regression line to the data failed. Any anticipated trend is perhaps masked by the fact that all of the discharge values have been area normalised for comparative purposes. The factors which affect the initial discharge are investigated further in Section 7.5.4 when a multiple regression technique is applied to the data set.

It would also be expected that larger catchments would be able to sustain baseflows for longer periods than the smaller catchments and hence would have longer recession durations. This could not be confirmed with a scatter plot and attempts to fit a successful regression line to the data failed. Elimination of the larger sized catchments (>10000 $km^2$) from the data set failed to improve the success of the regression. The factors which affect the initial discharge are investigated further in Section 7.5.4 when a multiple regression technique is applied to the data set.

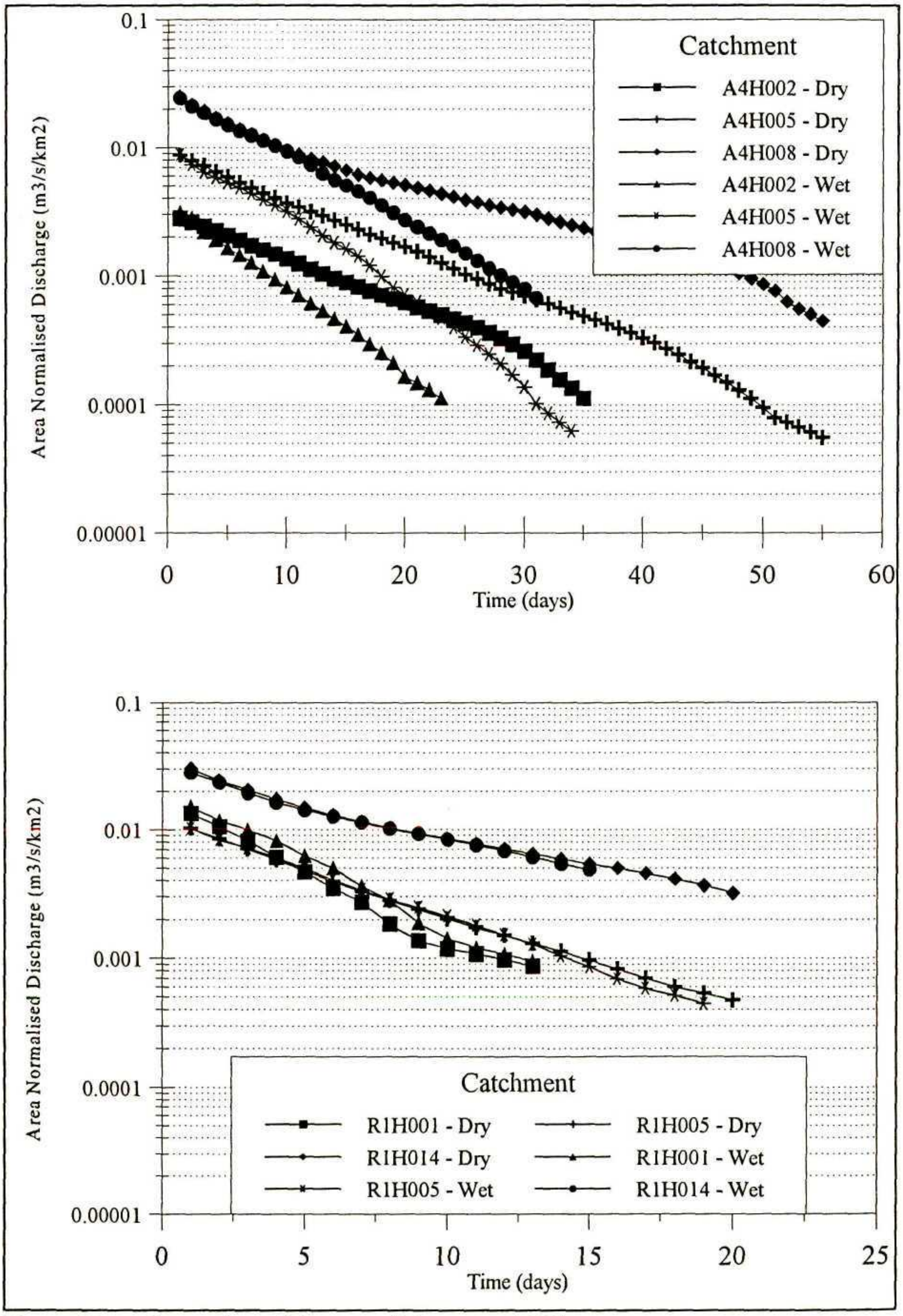


**Figure 23**: Comparison of the wet and dry season MRCs

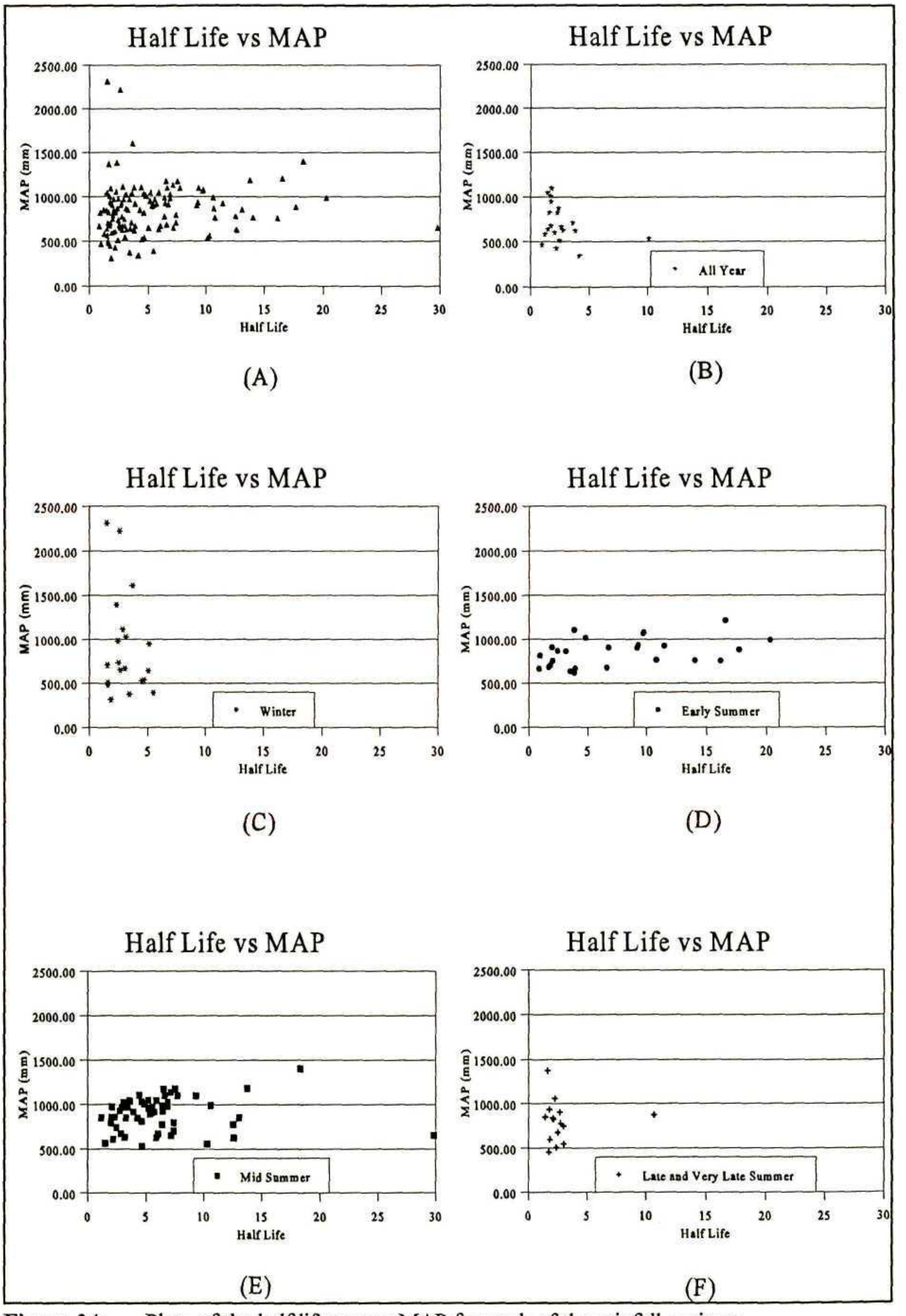


**Figure 24**: Plots of the half life versus MAP for each of the rainfall regions

## 7.5 Regionalisation of the Results

In order to establish trends and regionalise the information the MRCs had to be grouped in some manner. The relative positions and shapes of the MRCs within each group then had to be explained by the catchment characteristics.

### 7.5.1 Drainage Region

Initially the catchments were grouped according to drainage region. The graphs illustrating the MRCs per drainage region are provided in Appendix 3.3. While this provides a convenient means of grouping the catchments it is, however, artificial. In certain instances, such as in drainage regions A and B illustrated in Figure 25, the results appeared to be promising while in others, like drainage regions G and H, the results were far less convincing. In neither instance could the relative shapes or positions of the MRCs be reconciled with the catchment characteristics. However, it was noted that in drainage regions such as A and B the catchments had similar catchment characteristics *eg.* MAP. Hence it was decided that one of these characteristics should be used to group and regionalise the data as these factors have more physical meaning and are not limited by the same constraints as the catchment boundaries.

### 7.5.2 Shape of the MRC

Before this regional grouping according to catchment characteristics was undertaken, an alternative grouping according to shape and duration of the MRC was attempted. In order to group the MRCs in terms of similar shape, a means of describing the shape had to be found. A graphical means which involved the plotting of all of the MRCs on semi-log axes of identical magnitude was attempted. The first and last discharge value of the MRC were joined by a line and depending on the shape of the curve relative to the line the MRCs were grouped. While a number of groups of similar shaped curves were established, the patterns defined by these MRCs could not be explained by the catchment characteristics. The results were also difficult to apply owing to a lack of spatial continuity with catchments being located across the country. For the sake of brevity not all of these groups of MRCs are provided in the Appendices. Instead, an example of the types of different groups established is provided in Figure 26.

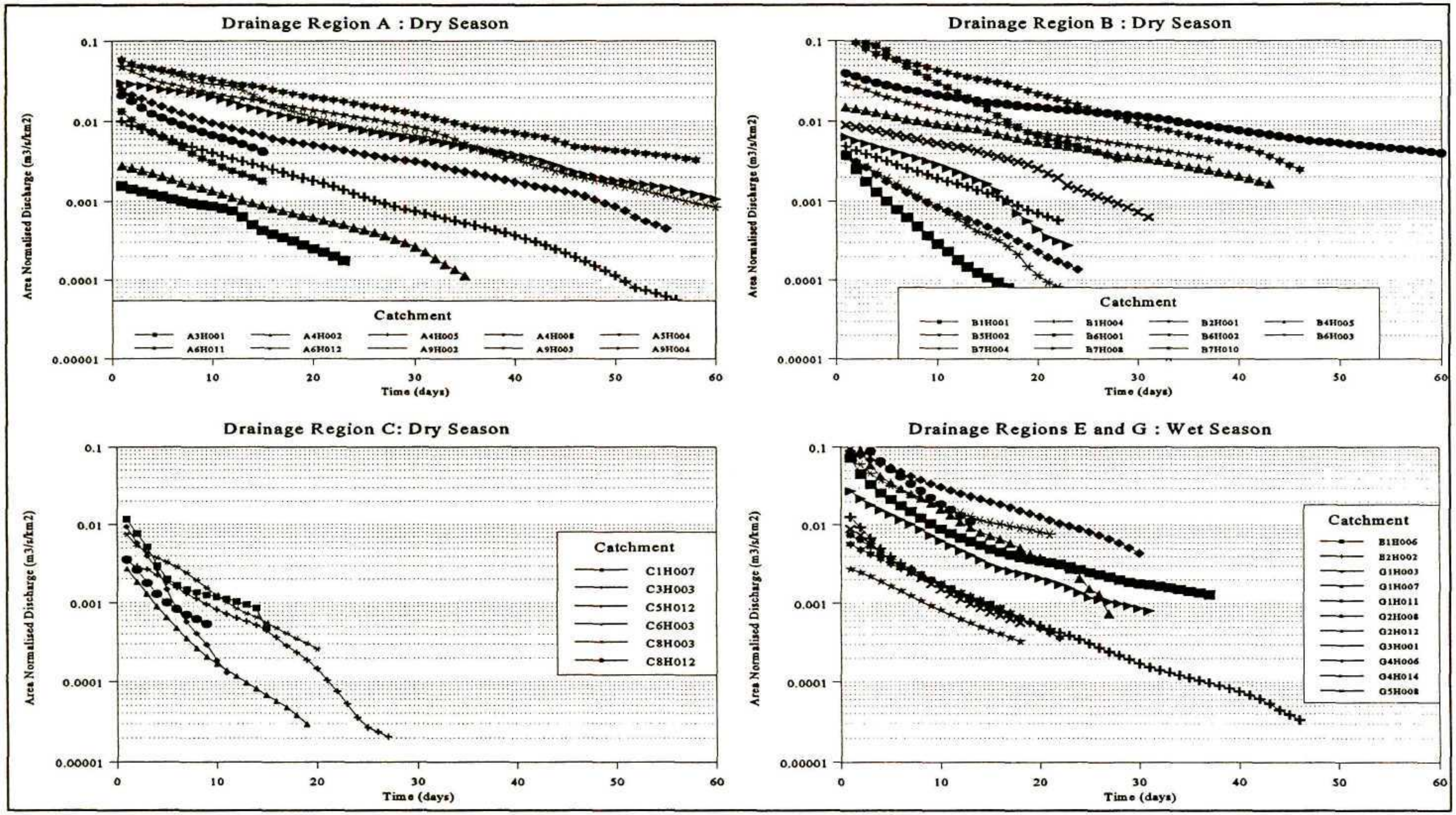


Figure 25: Example of the MRCs per drainage region

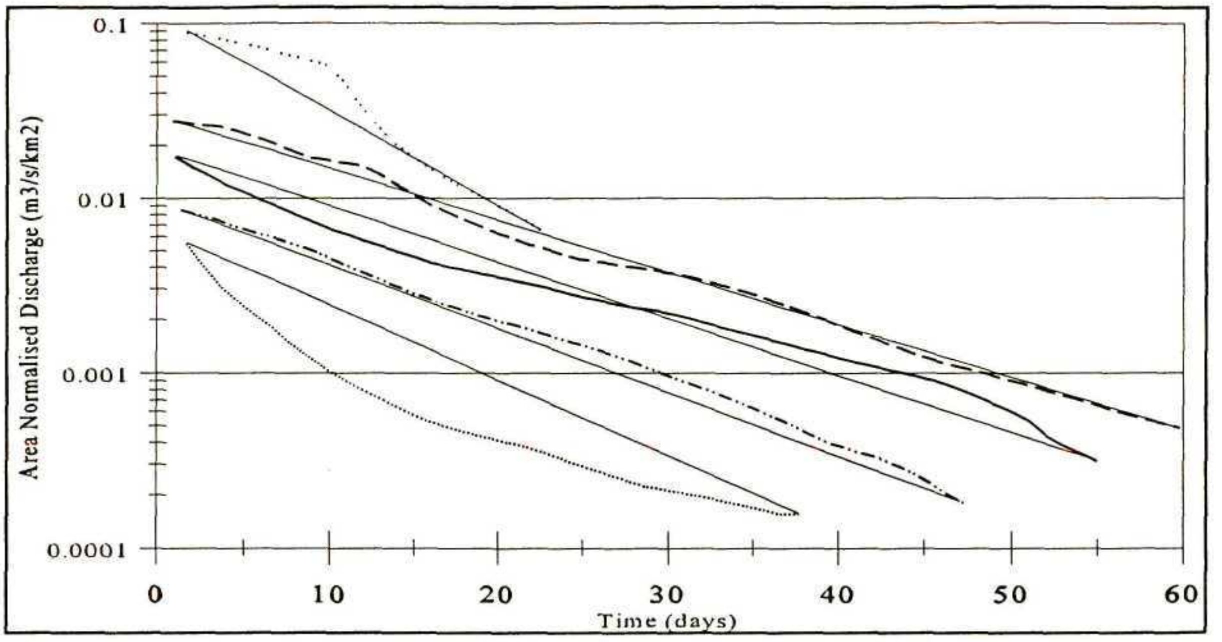


**Figure 26**: Examples of some of the MRC shapes that were identified

### 7.5.3 Climatic Variables

The climatic variables of MAP, rainfall concentration and rainfall seasonality were used in an attempt to group the MRCs. Combinations of these variables were also used.

(a) Mean annual precipitation: The data set was divided into three groups representing low (<600 mm), medium (600-1000 mm) and high (>1000 mm) MAP.

(b) Rainfall concentration: The data set exhibits a natural clustering in terms of rainfall concentration into three broad groups, namely, <15 %, 30 to 40 % and 41 to 60 %.

(c) Rainfall seasonality: The rainfall seasonality values calculated using the *ZONALSTATS* procedure (*cf.* Section 6.6.4) were used to divide the catchments into smaller groups. Owing to the simple nature of the classification, distinct groups are realised.

The graphs illustrating the groups defined above are given in Appendix 3.4. Of the three climatic variables, rainfall seasonality appears to be the most promising in terms of regionalisation as each seasonality value, on the whole, has a limited regional extent. This is illustrated when one considers that all of the catchments in drainage region G occur within the winter rainfall region.

Hence this variable has a distinct advantage over, for example MAP, as areas with similar MAPs are not necessarily adjacent to each other. However, on inspection the groups established for each of the variables displayed a large degree of overlap which suggests that there may be little difference between them. This was confirmed as the trends of the MRCs within each of these groups could not be explained by the remaining climatic or catchment characteristics. Consequently, the usefulness of these climatic variables by themselves in regionalising the data is doubtful.

(d) Combinations of climatic variables: Owing to the failure of the grouping using a single climatic variable, it was decided that a combination of climatic variables may yield more promising results.

Firstly the catchments were divided into groups of low (<600 mm), and high (>600mm) MAP. Subdivision into low, medium and high MAP groups resulted in too few MRCs when the rainfall seasonailties were considered and hence were not used. The low and high MAP groups were then subdivided further according to whether the rainfall seasonality was predominantly summer, winter or all year round. Figure 27 depicts the MRCs for catchments with high and low MAP within the all year round rainfall seasonality areas. It may be noted that there are no significant differences between the two sets of MRCs either in terms of shape, duration or position. Once again this methodology for the grouping of the catchments was not providing readily explicable results.

A plot of rainfall seasonality versus rainfall concentration provides a further basis for division of the catchments into smaller groups. Both of these variables display an inherent clustering or grouping and therefore when the two are plotted against each other a number of groups are identified. This plot is provided in Figure 28 where the various groups are labelled. The trends of the MRCs within each of these groups could, however, not be explained by the catchment characteristics. As an example of this failure, MRCs for groups two and three are provided in Appendix 3.5.

A plot of MAP versus rainfall concentration reveals no apparent trend. Minor clustering is exhibited owing to the clustering in the rainfall concentration values. This plot is provided in Appendix 3.6.

Having failed to establish groups for the MRCs using the climatic variables, a similar exercise using the catchment characteristics was undertaken.

### 7.5.4 Morphological Variables

Area, average slope and drainage density are the catchment characteristics that are used in this study. These were grouped as described below.

(a) Catchment area: The data set was divided into three groups representing small (<200 $km^2$), medium (200 to 1000 $km^2$) and large (>1000 $km^2$) catchments.

(b) Average catchment slope: The data set was divided into five groups representing slopes of 0 to 3°, 3 to 7°, 7 to 10°, 10 to 15° and greater than 15°.

(c) Drainage density: The data set was divided into three groups representing drainage densities of less than 0.1, 0.1 to 0.5 and greater than 0.5 $km/km^2$.

Each of the attempts, described above, to divide the data set into meaningful groupings met with limited success. Not only do the various groups overlap, which suggests that no apparent differences exist between the groups, but the trends which the MRCs within each of these groups exhibit could not be explained by the remaining climatic and morphological variables. Examples of the graphs described above are illustrated in Appendix 3.7.

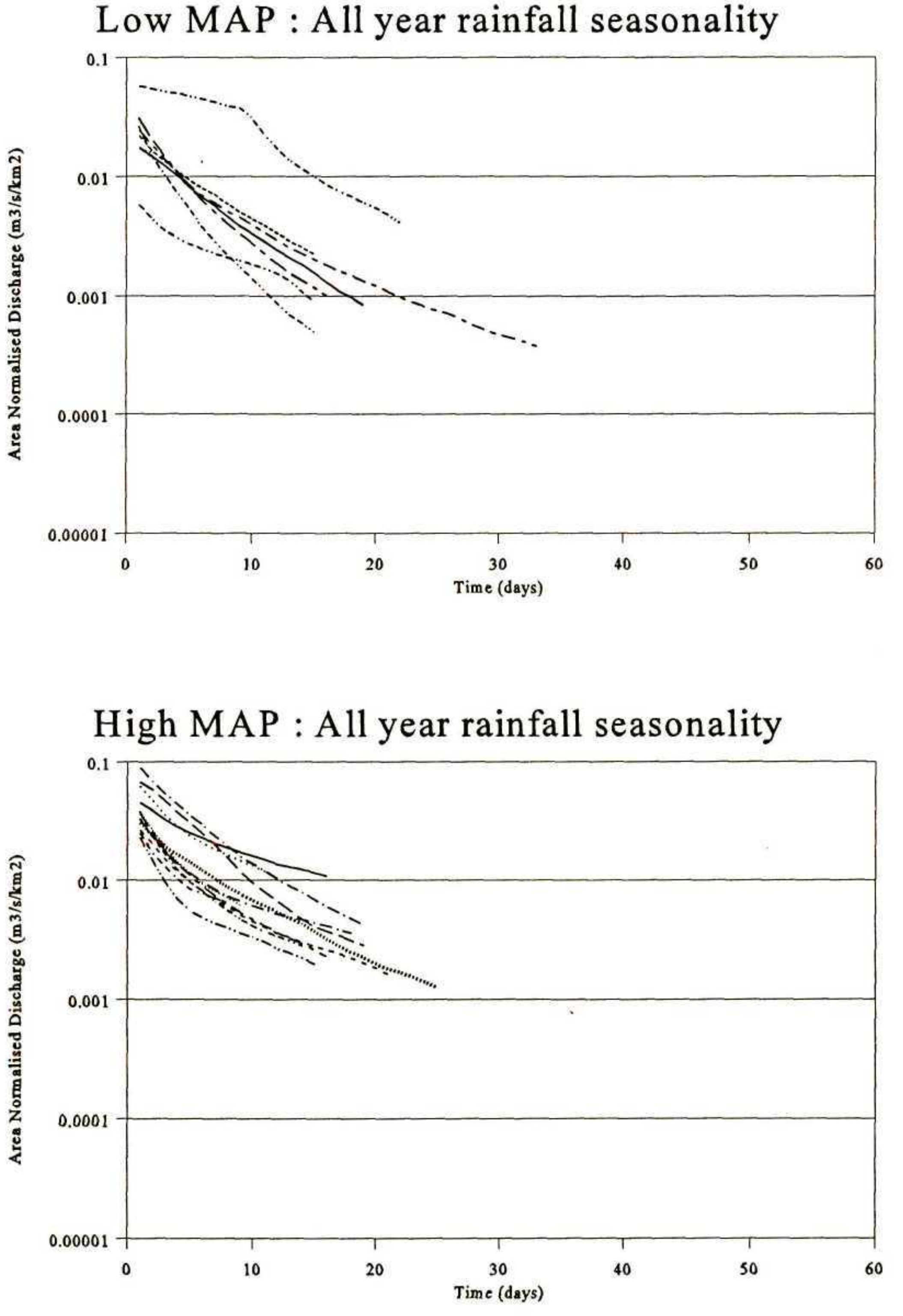


**Figure 27**: Comparison of the MRCs for low and high MAP catchments within the all year rainfall seasonality regions

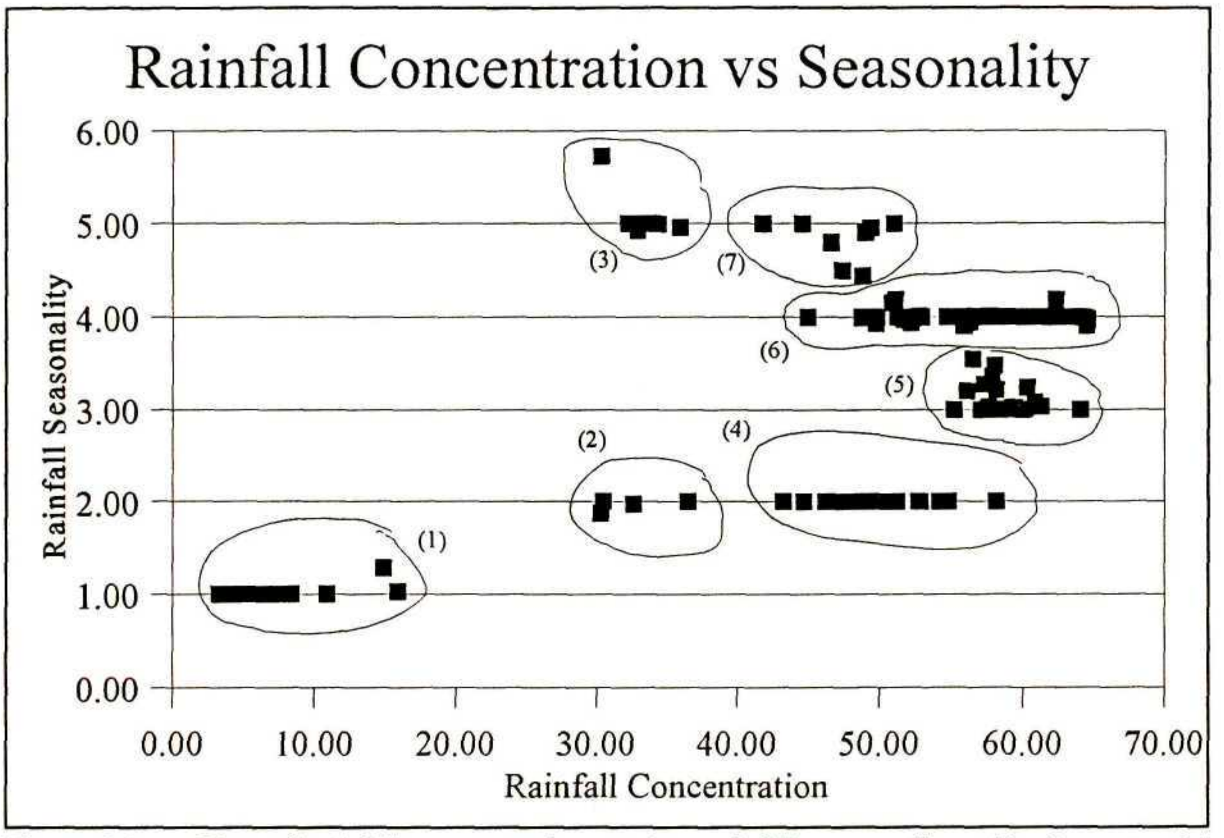


**Figure 28**: Plot of rainfall concentration against rainfall seasonality with the potential groupings demarcated

### 7.5.5 Geology

The effects which geology exerts on the groundwater regime and consequently on baseflow have been discussed in Section 3.2. Owing to the failure of other climatic and catchment variables to group the catchments, and acknowledging the importance of geology when considering baseflow, the geology was used in an attempt to group the catchments.

#### 7.5.5.1 Initial Geological Investigation

Initial grouping according to geology met with limited success. All catchments which contained more than 80% of a single specific lithology were selected and grouped. Examples of these geological groupings according to rock type (*eg.* 3) and lithology (*eg.* Ost) are provided in Appendix 3.8. While many of the groupings appeared to be distinctive, for example 3 OSt, it was not possible to explain the trends observed using the climatic and catchment characteristics.

A possible reason for the failure of the initial geological investigation is the assumption that the minor portion of geology constituting less than 20% of the catchment does not affect the MRC to the degree that it warrants consideration. As a result the investigation was repeated and the lithology which constitutes this minor portion of the catchment was also considered. The investigation was also broadened to include all combinations and proportions of lithologies under consideration.

#### 7.5.5.2 Broadened Geological Investigation

The ability of geological characteristics to account for trends exhibited by the MRCs is described below. Accompanying MRCs annotated with the proportion of each lithology are also provided. The proportions listed are in the same order as the titles of the graphs, for example, a label of 40/60 attached to a MRC on a graph labelled *Pe-Pa* represents 40% *Pe* and 60% *Pa*. Not all combinations of the various lithologies are discussed. The reason for this will become apparent from the examples which are provided.

*Pe* represents the Ecca Group shales which are unmetamorphosed and undeformed. A single catchment was underlain solely by this lithology, as illustrated in Figure 29.

*Pa* represents the Adelaide Subgroup which consists of mudstone and sandstone and exhibits minor degrees of metamorphism and moderate deformation. The curvilinear MRCs illustrated in Figure 29 exhibit minor variation and this is attributed predominantly to the presence of structure introduced by the deformation. Catchment size is also a factor to consider, as the smaller the catchment the less likely there is to be a close correspondence between the surface and groundwater catchments. This is likely the reason why catchment R2H001 displays a shallower recession curve, as this catchment is relatively smaller than the rest of the catchments underlain by this lithology. Hence it is possible that the smaller catchment receives groundwater discharge from outside the catchment. The rate of recession of this lithology is faster than that of *Pe* and is attributed to the presence of the sandstone as well as the structure introduced by the deformation.

*Pes* also represents the Ecca Group shales, however, sandstone units are interbedded with the shales. This lithology displays minor metamorphism and no deformation. Unfortunately, no catchment was located on this lithology alone and hence no comment regarding MRCs from this lithology may be made. When the combination of *PePes*, as illustrated in Figure 30, is considered it was noted that the greater the proportion of *Pes* the steeper the curvi-linear recession. This is attributed to the increased proportion of sandstone within the catchment.

When the combination of *PePa* is considered it was noted that the recessions are curvilinear as illustrated in Figure 30. Despite minor variation there appears to be little difference between the MRCs as the proportion of *Pa* increases to 36%. The minor variation may be attributed to differences in structure resulting from the deformation. However, for the two catchments where more than 40% of the catchment consists of *Pa* and to a lesser extent *Trt* (*cf. PaTrt*) the recessions are steeper. Both *Pa* and *Trt* contain sandstones and this increase in the steepness of the recession curves is in part attributed to their increased presence, along with the structure introduced by the degree of deformation.

The *PePaPes* combination given in Figure 31 once again indicates that as the proportion of sandstone bearing and deformed lithologies increases there is a steepening of the curvi-linear recession curves. The values within parentheses provide the *Pe(PaPes)* proportions.

However, the *PaTrt* combination does not provide results which are as readily explicable as those described above. It will be noted that the trends of the MRCs illustrated in Figure 32 are quite erratic. *Trt* represents the Tarkastad subgroup which consists of mudstone and sandstone and exhibits no metamorphism or deformation. The lack of trends observable within the MRCs may possibly be ascribed to the varying proportions of sandstone and mudstone. The lithological groups of *Pa* and *Trt* defined by Vegter (1995) are broad classifications and are unable to account for these natural variations in the proportion of the two rock types. The presence of structure within the *Pa* lithology may be a further complicating factor. *Trmc* represents the Molteno, Elliot and Clarens Formations which consist of sandstone, siltstone, mudstone and shales. This lithological group exhibits no metamorphism or deformation. The two MRCs which represent a *PaTrtTrmc* combination indicate that where *Trt* is very dominant, such as 97% of T2H002, the potential to sustain long shallow recession curves is enhanced. The presence of *Trmc* is difficult to evaluate owing to the limited number of MRCs.

The results described above indicate that geology the different trends defined by the MRCs may be discriminated by geological attributes with reasonable success. This success, however, serves more to highlight the importance of geology than provide a useable methodology for the grouping of MRCs. The reason for this is related to the limited number of lithologies underlying the catchments under consideration. Vegter (1995) identified 86 lithostratigraphic water bearing units for South Africa. The catchments utilised during this study are underlain by only 41 of these 86 lithostratigraphic units. Of these 41 lithostratigraphic units which are encountered, very few of them occur as a single lithology underlying a catchment. Most of them occur in combination with other lithologies, which makes it very difficult to assess the relative effects which each lithology exerts on the MRCs. Added to this is the fact that most of the lithologies present within this study exhibit some degree of deformation. Deformation introduces structures which either disrupt or enhance the baseflow recession process, as discussed earlier in Section 3.2. Varying degrees of deformation thus complicate the relationships which are being derived. A further complicating factor is the varying proportion of rock types encountered in each of the lithologies. Lithostratigraphic units such as the Molteno Formation are thick sedimentary packages consisting of alternating beds of sandstone, siltstone and mudstone. These beds have variable thickness and lateral persistence. Consequently, the location of the catchment within these sediments both spatially and vertically will affect the proportions of each rock type present within the catchment. The proportions of each rock type will in turn affect the baseflow regulating capacity of the catchments.

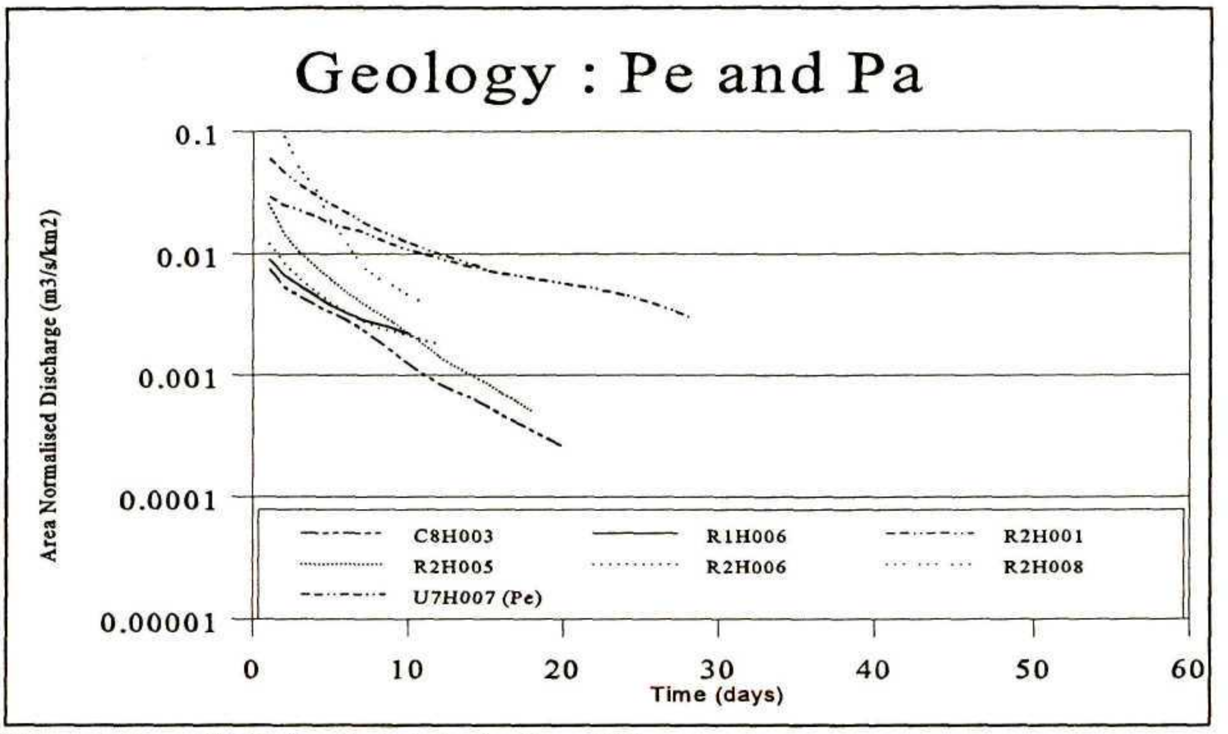


**Figure 29**: MRCs for the lithologies *Pe* and *Pa*

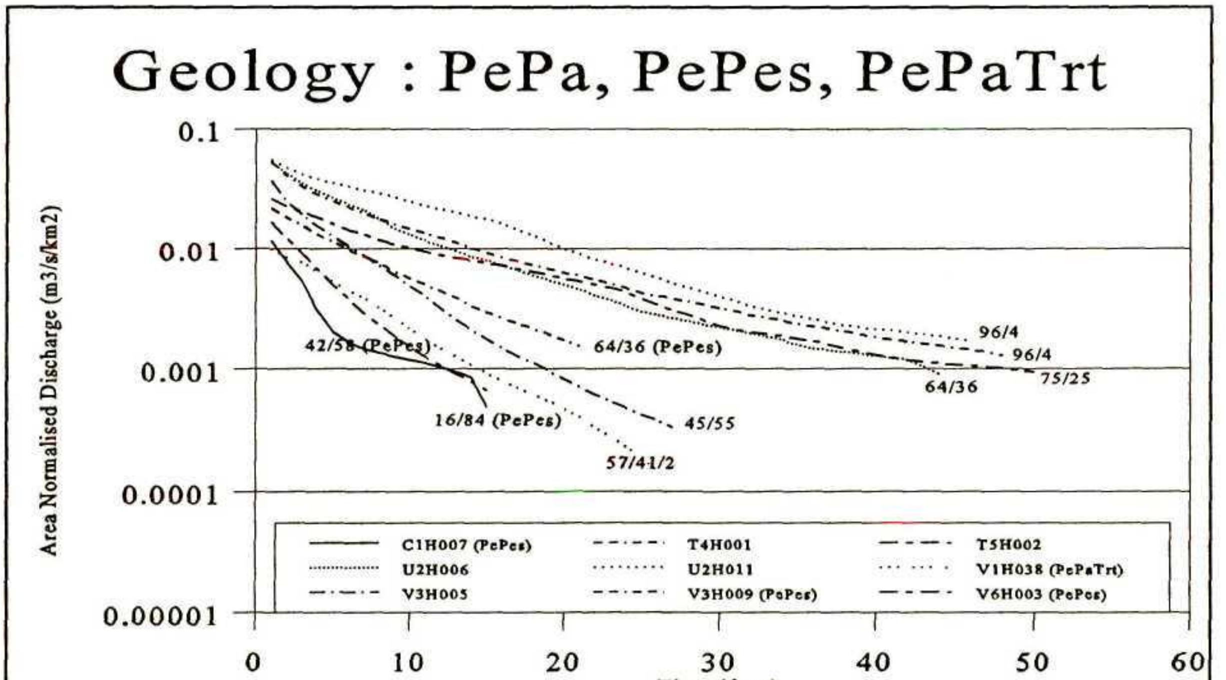


**Figure 30**: MRCs for the lithologies *PePa*, *PePes* and *PePaTrt*

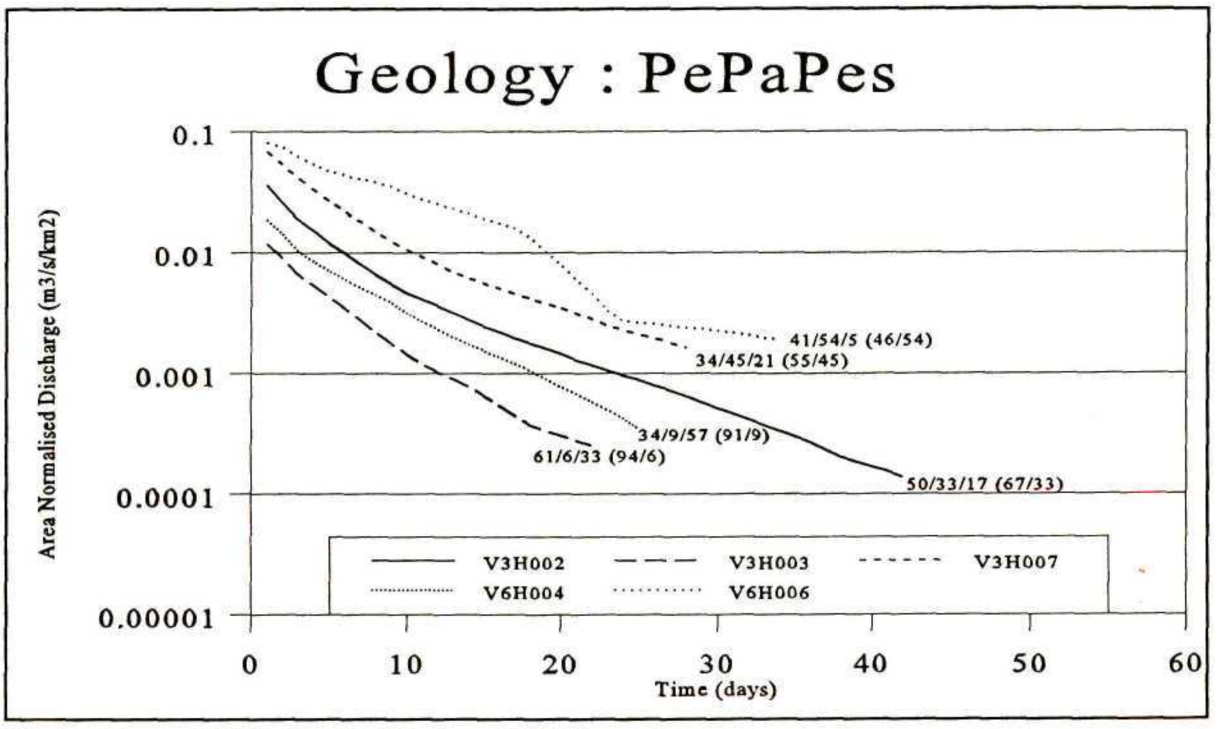


**Figure 31**: MRCs for the lithology *PePaPes*

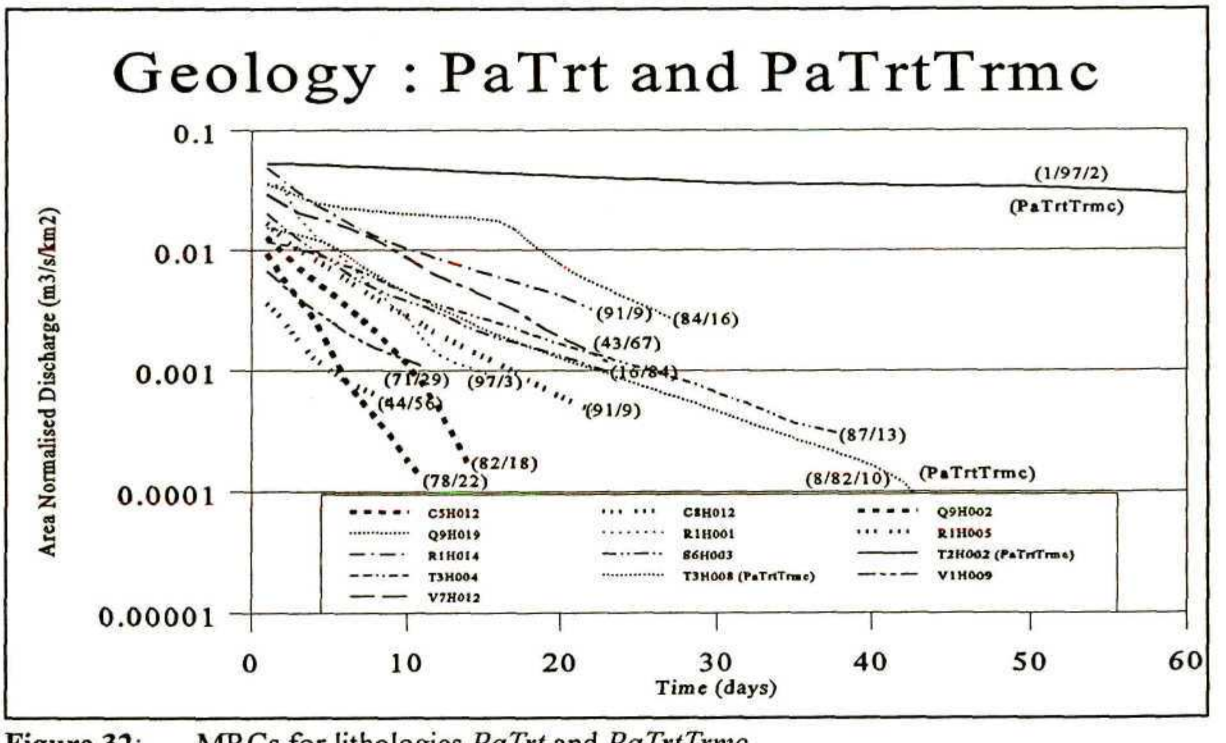


**Figure 32**: MRCs for lithologies *PaTrt* and *PaTrtTrmc*

## 7.6 Multiple Regression Analysis

Owing to the limited success achieved using the rather empirical techniques described above statistical techniques were employed in order to determine which of the catchment and climatic parameters account for the variance in the data set. It was hoped that the statistical analysis would either highlight results which had not been readily observed using the empirical techniques or that it would verify that the data are highly variable and that there are little or no trends to be observed. It was not the intention of the study to develop a statistical model which may be used for predictive purposes. In order to utilise the technique of multiple regression a suitable dependent variable is required. In keeping with the non-assumption of exponential recession the recession constant, K, could not be used as is generally the case in investigations of this nature. As has been suggested by many researchers, the half life offers a physically meaningful alternative to the recession constant (*cf.* Section 4.5.5). Although it has received limited attention in the literature the log life may also be used as an alternative. Both of these recession durations were calculated for each of the MRCs and used as an independent variable in the stepwise multiple regression analyses using *GENSTAT* Version 3. This stepwise process requires that a full model be fitted and that the variable with the lowest non-significant students *t* value be dropped and the model refitted. This process is repeated until the final model accounts for the most variance possible and each of the remaining variables has a significant students *t* value.

The independent variables used when fitting the regression model include MAP, rainfall seasonality, rainfall concentration, catchment area, average catchment slope, drainage density, *ACRU* simulated recharge, Vegter's recharge values and the geological index. The dependent variables used were half life, log life and $Q_0$. These dependent variables are provided in Appendix 3.9.

### 7.6.1 Correlation matrix

At the outset a correlation matrix of the variables under consideration was produced. This matrix is provided in Appendix 3.10. The following observations were made regarding the correlation matrix.

(a) The log life is well correlated with the half life.

(b) The rainfall concentration is well correlated with the rainfall seasonality.

(c) Both of the recharge estimates are well correlated with the MAP.

(d) The *ACRU* simulated recharge is moderately correlated with Vegter's recharge values.

(e) The initial discharge is well correlated with the average catchment slope and moderately correlated with the MAP.

Further comment regarding these observations will be made within the relevant Sections below, where the results from the multiple regression analysis typically highlight similar relationships.

### 7.6.2 Half Life

The half life was used as the dependent variable. The full model fitted included MAP, rainfall seasonality, rainfall concentration, catchment area, average catchment slope, drainage density and the geological index. The final model fitted included MAP, rainfall concentration and the geological index and accounted for 23.5 % of the variance of the half life.

The initial model did not include either of the recharge values. The recharge values are likely to be well correlated with several of the other variables and are either simulated or estimated values and as a result were not included in the first stepwise multiple regression models. In order to determine if they affect the final models already derived, or if they are able to improve the amount of variance accounted for by the model the stepwise regression process was repeated.

Firstly the *ACRU* recharge values were used along with the full model described above. The final model fitted included the rainfall seasonality, the *ACRU* recharge value and the geological index. These variables accounted for 25.0 % of the variance.

The initial discharge was found to be affected by the MAP and the catchment slope. These results are consistent with what one would expect. Likewise the duration of the recession is affected by factors which are consistent with what one would expect where the supply of groundwater is determined by the MAP and the groundwater recharge and the geology is responsible for its regulation. The regression analysis also highlights that real data is unlikely to conform to expected trends. While the MRC represents the average baseflow condition it would perhaps be better to calculate an average value for each of the characteristics determined from the MRCs, for example the half life. Other reasons which may account for the lack of expected results are those summarised in Section 4.6.

# 8. DISCUSSION AND CONCLUSIONS

Baseflow periods of streamflow will provide the limiting threshold in terms of water quantity and quality as the population of South Africa grows and develops. The accurate modelling of these baseflows is thus of paramount importance and was the subject of this study.

Literature regarding baseflow indicates that researchers tend to assume that the catchments they are modelling conform to exponential recession theory. They also appear to prefer statistical techniques for the prediction of baseflows at the ungauged site. Alternatively, they utilise hydraulic models which require specialised inputs, for example specific yield. The current study could not make broad assumptions, nor could it follow conventional techniques, as there were several factors that needed to be considered. The results of the study were not merely to be informative but were required to be of such a nature that they could be utilised to upgrade the current *ACRU* baseflow generation and regulation routines. Since the *ACRU* model is a deterministic daily time-step model, a statistical analysis would prove difficult to incorporate into its structure. Hydraulic models are also problematic as reliable estimates of specialised groundwater variables are not readily available within South Africa. The current study also aimed to investigating the shape of the recession curves and determining the validity of an exponential model of baseflow recession. Hence, it was decided that the research was to be conducted in a truely investigative manner, making as few assumptions as possible, utilising as good a data set as could be obtained and making use of new methodologies if need be, such that a set of rules governing baseflow recession within South Africa could be established. These rules were to be incorporated into the *ACRU* model in the form of a Baseflow Decision Support System.

Having established a streamflow database consisting of catchments which are deemed to be recording natural flows, it is clear that the size of the data set is limited. This problem is exacerbated by the exclusion of certain catchments from the study and hence every effort should be made in future to increase the size of the database. Following a literature review a number of factors were identified as having an effect on baseflow recession. These were used in this study and include catchment area, average catchment slope, drainage density, mean annual precipitation, rainfall concentration, rainfall seasonality, simulated and estimated annual groundwater recharge and a geological index. Estimates of these factors were determined for each catchment and constitute the database for catchment characteristics. The results, or lack thereof, suggest that either the factors selected are not representative, *ie*. there are other factors which need to be considered, or that the actual streamflow data are highly variable, or that the natural system is so complex that it requires more sophisticated methods of analysis.

The results also indicate that the majority of rivers in South Africa do not conform to simple models of baseflow recession. Consequently, simple exponential baseflow recession models should be used with caution within South Africa. This observation has implications for current and future modelling with the *ACRU* system. Attempts to explain the trends exhibited by the MRCs in terms of catchment characteristics and to regionalise the results achieved limited success. Geology appeared to provide the greatest success in the graphical analysis and was commonly selected as a significant variable in the multiple regression analysis. These results suggest that the effects of geology on baseflow recession should be pursued further in the future. The variability exhibited by the results is ascribed to the high degree of variability within the data set. This variability is evident not only when one conducts the graphical analysis but also when one utilises statistical analytical techniques. Common causes of such variability were outlined in Section 4.6 , however, the complexity of the catchment geology is believed to be the primary cause. If one considers the influence that the presence of a single fault or dyke across a catchment is likely to exert on the groundwater regime and consequently the baseflow, the contribution of complex geology to this variability is clear. Owing to the lack of readily useable results it was concluded that until further results were forthcoming the development of a rule based model for baseflow recession analysis in South Africa would be premature.

These results are consistent with those obtained by other researchers investigating baseflows within South Africa. Smakhtin *et al.* (1995) found from the mapping of low flow characteristics for South Africa that these exhibit a high degree of spatial variability. Even within the same drainage region and for catchments with a similar size and length of streamflow record, standardised low flow variables varied greatly. This suggests that baseflow characteristics are dependent on local physiographic factors and hence low flow investigations should be undertaken at a finer catchment scale resolution. Smakhtin *et al.* (1995) also note that attempts to regionalise low flows on a national basis using the available stations and quality of data are likely to meet with only limited success.

# 9. RECOMMENDATIONS FOR FUTURE RESEARCH

It is clear that baseflow periods of streamflow are complex and difficult to model. Investigators still have much research to conduct into this neglected component of streamflow. A large proportion of the time spent during this study was to procure data and the preliminary investigation of these results has been completed. However, the availability of these data lends itself to further investigation. A number of key areas of future research are identified.

(a) Having established and used the streamflow database it is clear that the size of the data set is limited. Every effort should be made to increase the size of the database.

(b) A greater number of catchment characteristics could be determined. The use of multi-variate analyses could be used to determine which factors are of importance in South Africa, thereby removing the reliance on results obtained in humid countries.

(c) The database consisting of the extracted recessions could be analysed further with the primary aim being the fitting of appropriate recession models. Determining the type of equations fitted most frequently may provide further insight and provide a means of modelling baseflow in South Africa.

(d) A more complete multivariate statistical analysis of the streamflow and catchment characteristic databases needs to be conducted. The current study indicated that there is instability in the variance and this needs to be considered further.

(e) Investigating the processes which control baseflow recession at the catchment scale would be of benefit to hydrological modellers. This would aid in linking surface and groundwater models that baseflow may be modelled in a more physical and conceptual method.

While the results from this study do not appear to be "ground breaking" they are believed to be encouraging and facilitate further research. Owing to the major role which geology plays in the generation and regulation of baseflow further collaborative research with other scientists, in particular geohydrologists, should be undertaken.

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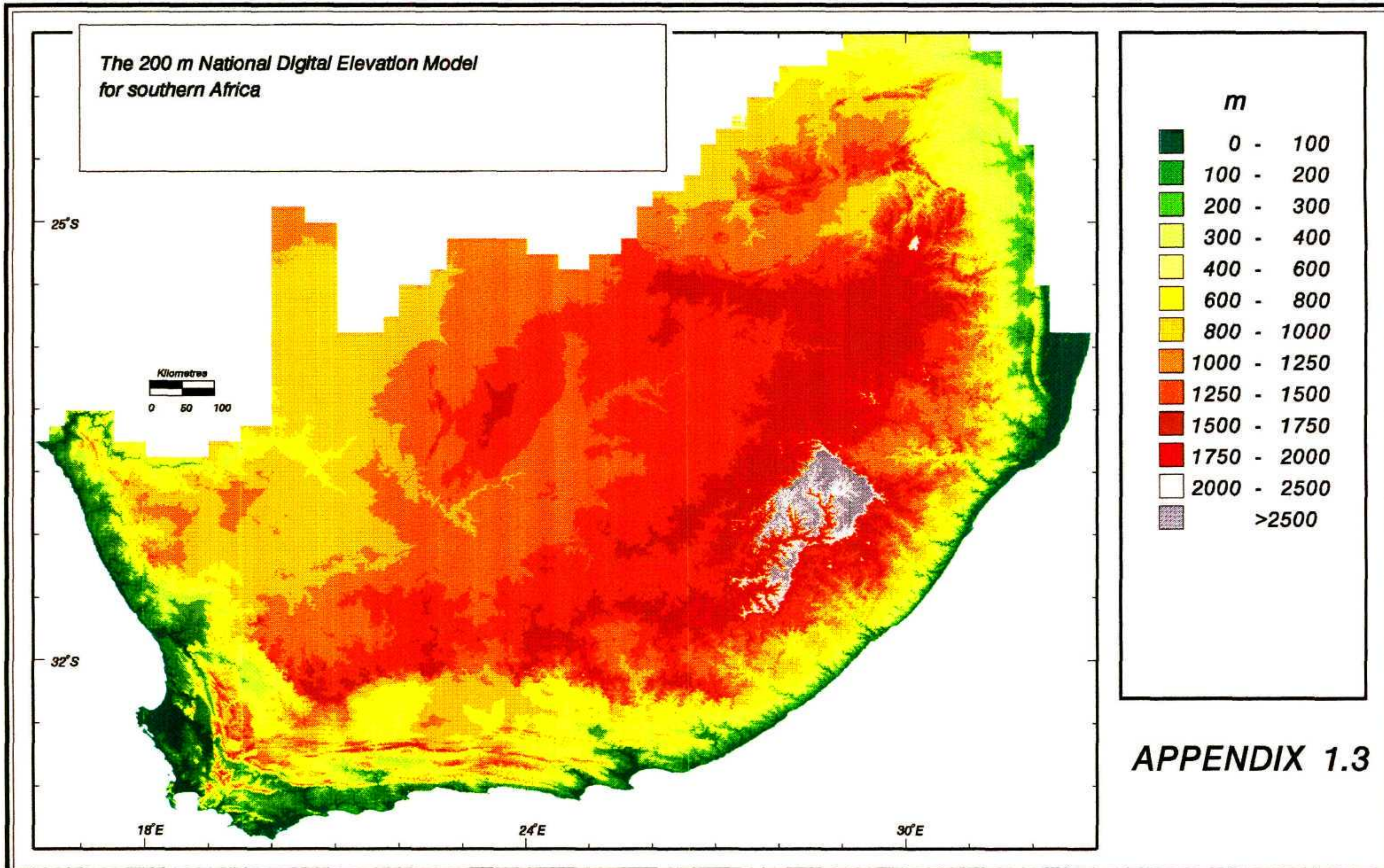
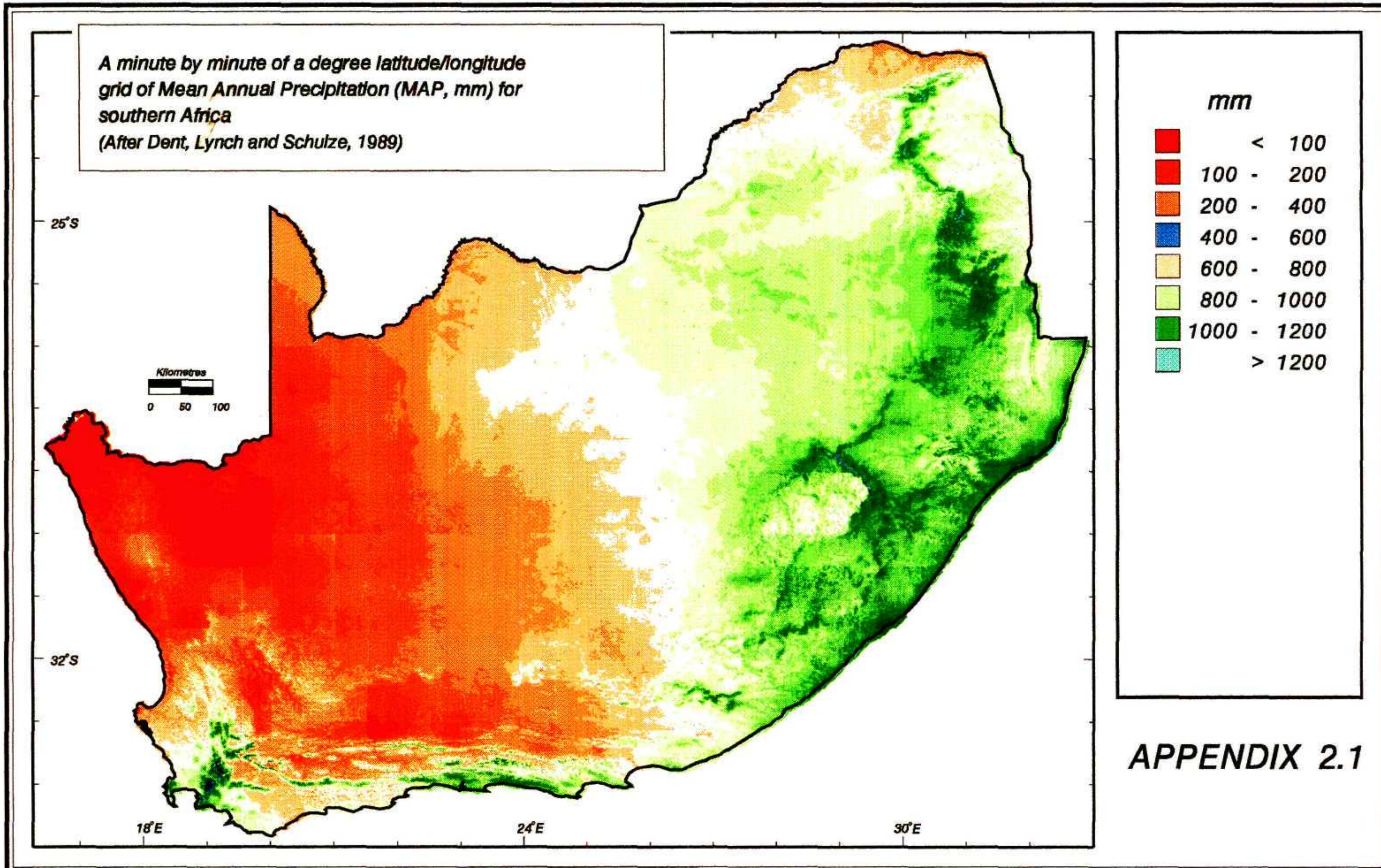
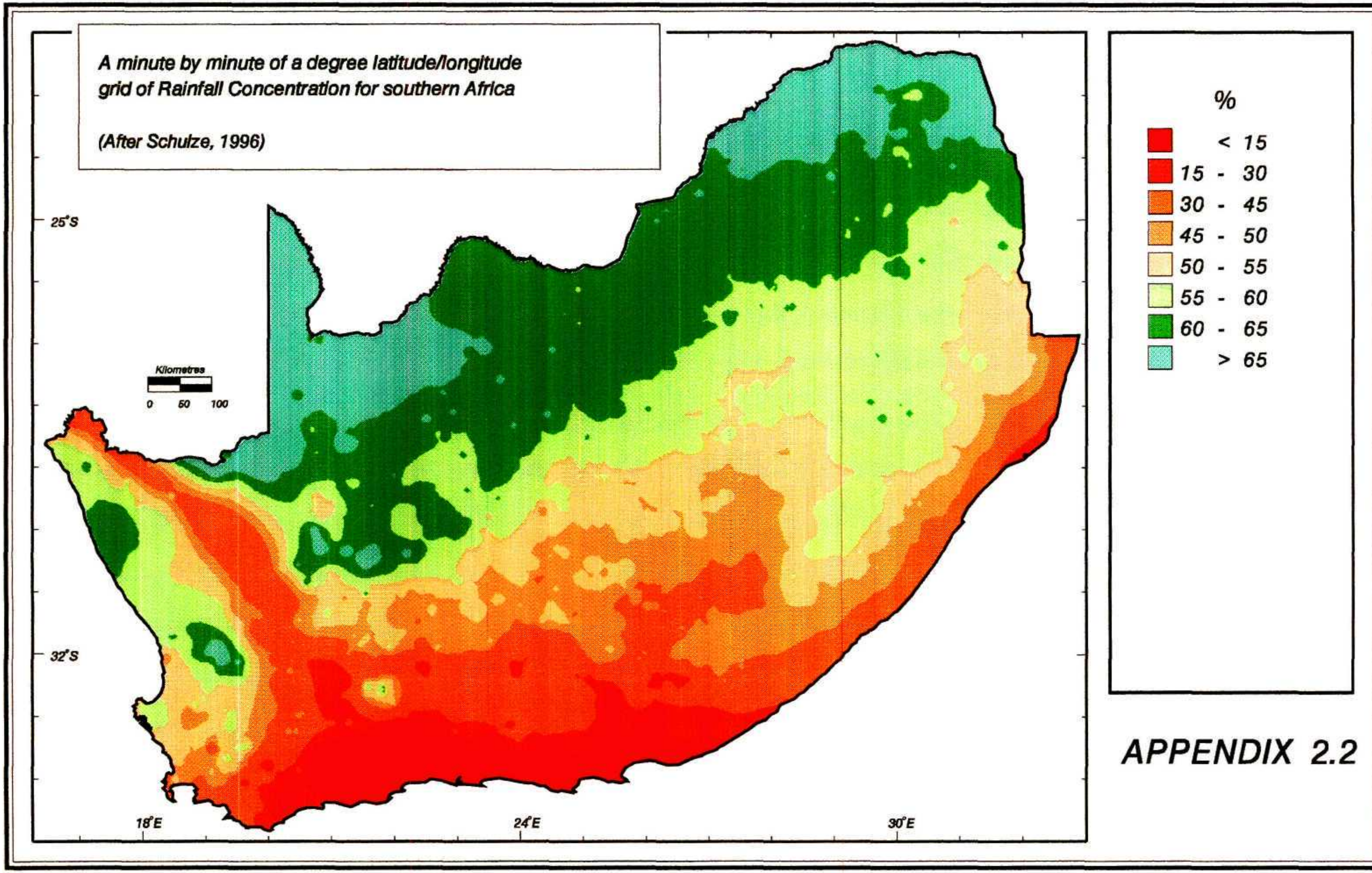


The 200 m National Digital Elevation Model
for southern Africa
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E
m
0 - 100
100 - 200
200 - 300
300 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1250
1250 - 1500
1500 - 1750
1750 - 2000
2000 - 2500
>2500

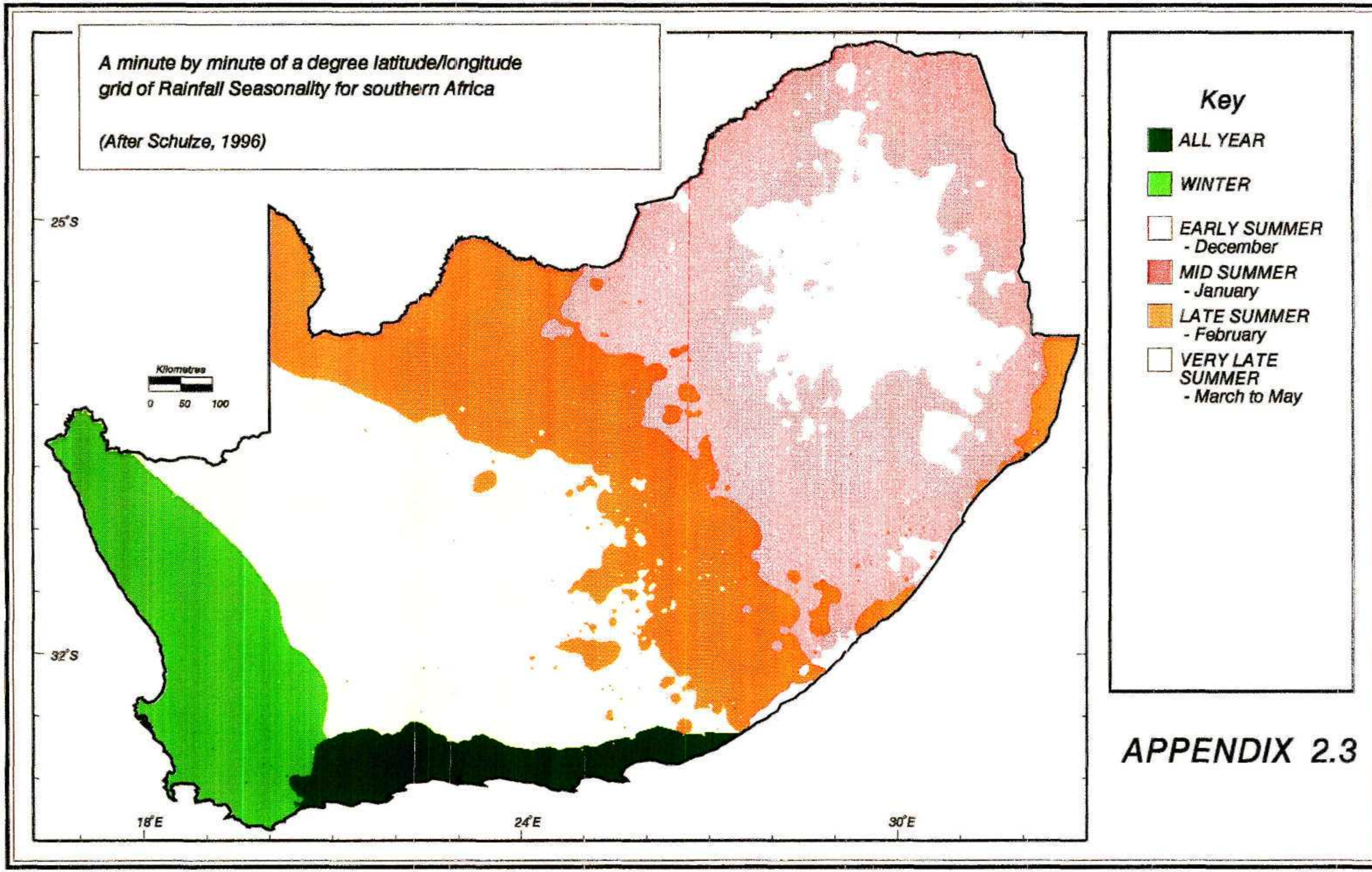

APPENDIX 1.3


A minute by minute of a degree latitude/longitude grid of Mean Annual Precipitation (MAP, mm) for southern Africa
(After Dent, Lynch and Schulze, 1989)
25°S
32°S
18°E
24°E
30°E
Kilometres
0 50 100
mm
< 100
100 - 200
200 - 400
400 - 600
600 - 800
800 - 1000
1000 - 1200
> 1200

# APPENDIX 2.1

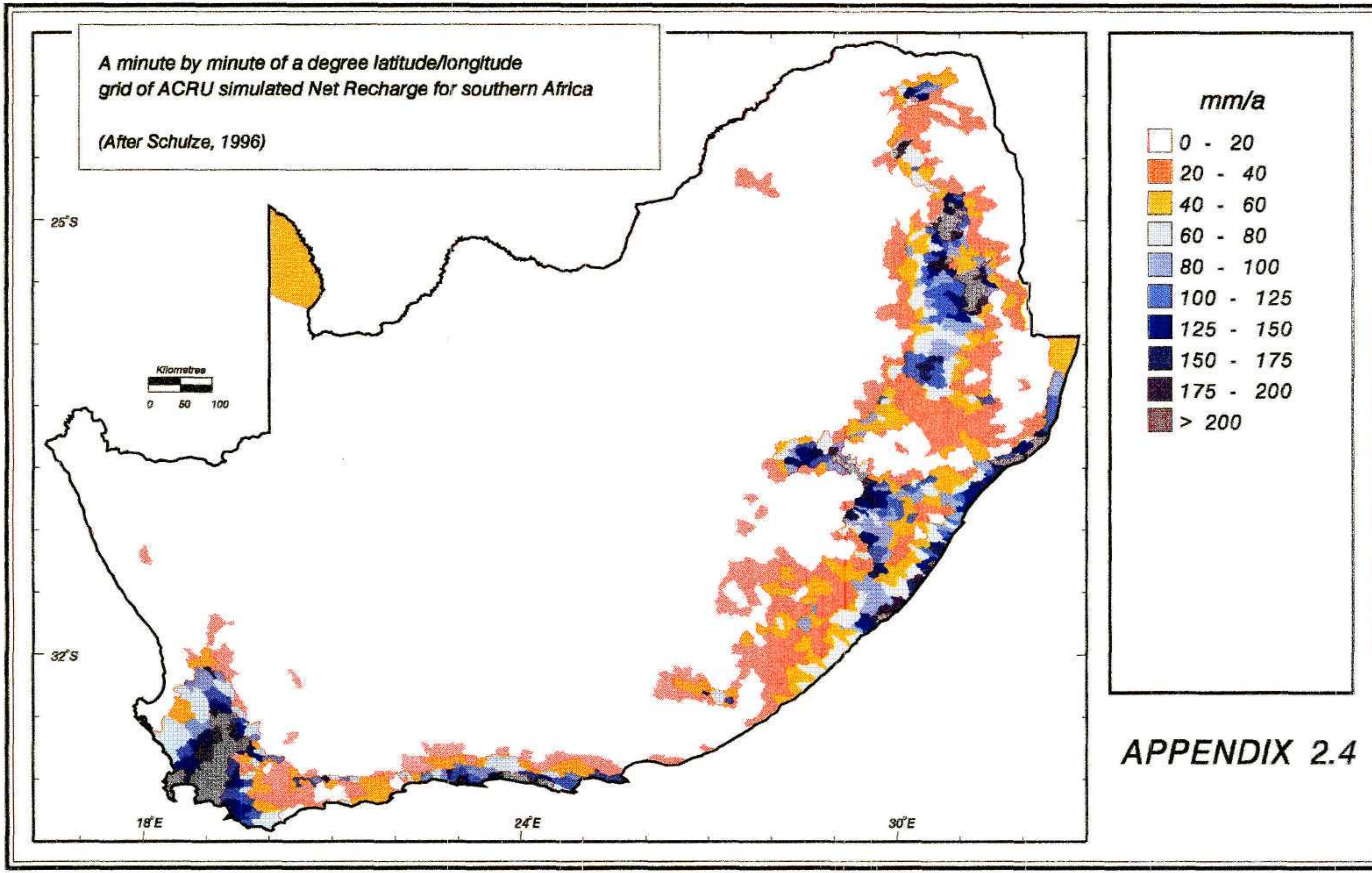

A minute by minute of a degree latitude/longitude
grid of Rainfall Concentration for southern Africa
(After Schulze, 1996)
25°S
32°S
18°E
24°E
30°E
Kilometres
0 50 100
%
< 15
15 - 30
30 - 45
45 - 50
50 - 55
55 - 60
60 - 65
> 65

APPENDIX 2.2

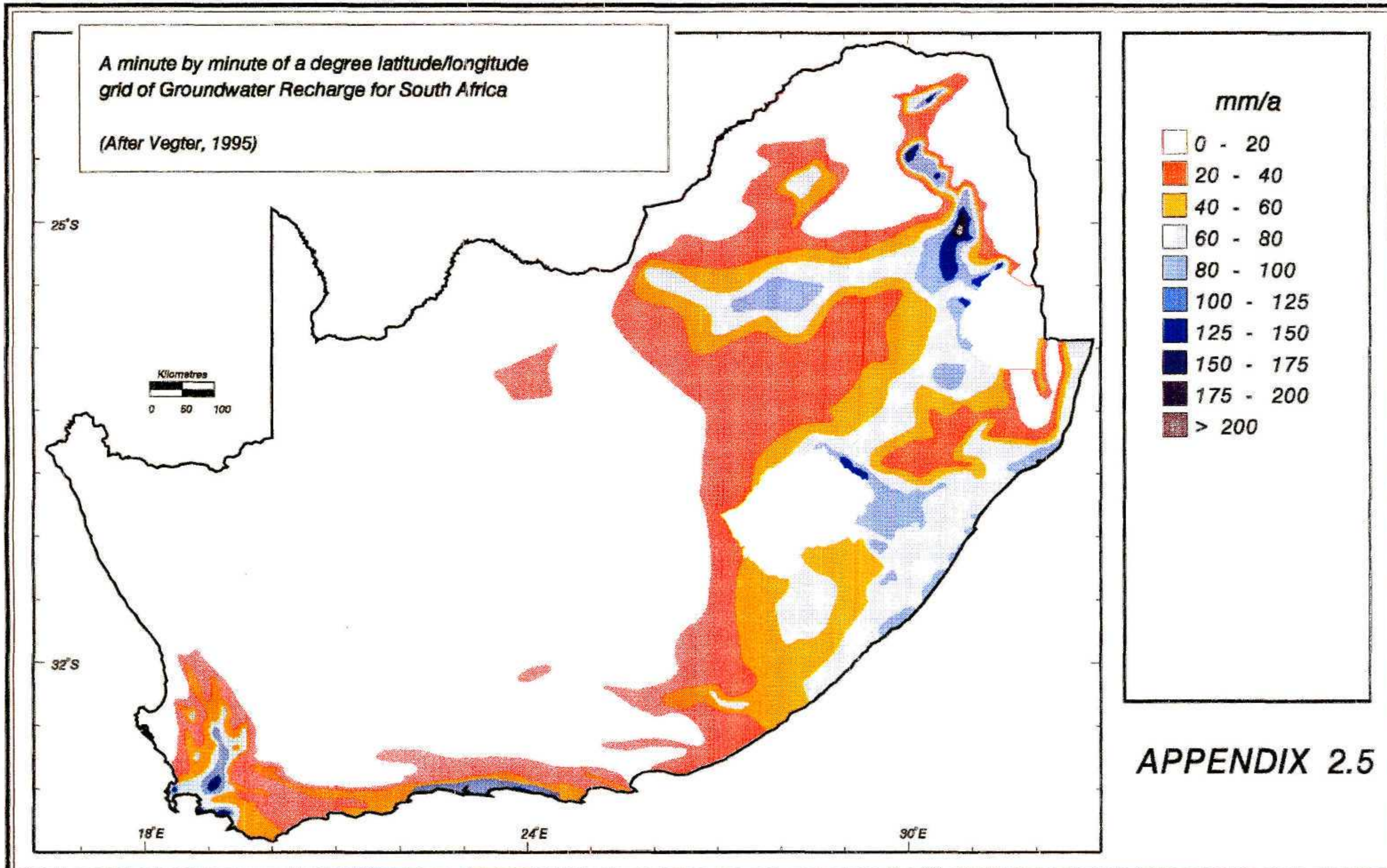

A minute by minute of a degree latitude/longitude
grid of Rainfall Seasonality for southern Africa
(After Schulze, 1996)
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E
Key
ALL YEAR
WINTER
EARLY SUMMER - December
MID SUMMER - January
LATE SUMMER - February
VERY LATE SUMMER - March to May

APPENDIX 2.3

# APPENDIX 2.4



A minute by minute of a degree latitude/longitude
grid of ACRU simulated Net Recharge for southern Africa
(After Schulze, 1996)
mm/a
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 125
125 - 150
150 - 175
175 - 200
> 200
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E


A minute by minute of a degree latitude/longitude
grid of Groundwater Recharge for South Africa
(After Vegter, 1995)
Kilometres
0 50 100
25°S
32°S
18°E
24°E
30°E
mm/a
0 - 20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 125
125 - 150
150 - 175
175 - 200
> 200

# APPENDIX 2.5

## 11. APPENDICES

**Appendix 1.1** : Department of Water Affairs and Forestry gauging weirs utilised

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| A2H029 | B6H002 | D5H003 | G5H008 | J3H017 | R1H006 | U2H013 | W4H004 |
| A2H032 | B6H003 | E1H006 | H1H007 | J4H003 | R1H007 | U3H002 | W5H001 |
| A2H039 | B6H006 | E2H002 | H1H013 | J4H004 | R1H014 | U4H002 | W5H004 |
| A2H049 | B7H004 | G1H003 | H1H017 | K3H002 | R2H001 | U7H007 | W5H006 |
| A2H050 | B7H008 | G1H007 | H1H018 | K3H004 | R2H005 | V1H001 | W5H008 |
| A3H001 | B7H010 | G1H008 | H2H001 | K3H005 | R2H006 | V1H002 | X2H005 |
| A4H002 | B9H001 | G1H009 | H2H003 | K4H001 | R2H008 | V1H009 | X2H008 |
| A4H005 | C1H007 | G1H010 | H2H005 | K4H002 | R2H012 | V1H010 | X2H010 |
| A4H008 | C2H026 | G1H011 | H3H001 | K4H003 | S3H006 | V1H031 | X2H011 |
| A5H004 | C2H027 | G1H012 | H3H004 | K5H002 | S6H003 | V1H038 | X2H012 |
| A6H011 | C2H028 | G1H014 | H3H005 | K6H001 | T1H004 | V2H001 | X2H013 |
| A6H012 | C2H065 | G1H015 | H4H005 | K7H001 | T2H002 | V2H005 | X2H014 |
| A6H018 | C2H067 | G1H016 | H4H012 | K8H001 | T3H004 | V3H002 | X2H015 |
| A6H019 | C3H003 | G1H017 | H6H008 | K8H002 | T3H008 | V3H003 | X2H022 |
| A6H020 | C5H007 | G1H018 | H6H010 | L1H001 | T3H009 | V3H005 | X2H024 |
| A9H002 | C5H008 | G2H008 | H7H001 | L6H001 | T4H001 | V3H007 | X2H025 |
| A9H003 | C5H012 | G2H012 | H7H003 | L8H001 | T5H002 | V3H009 | X2H026 |
| A9H004 | C6H003 | G3H001 | H7H004 | L8H002 | T5H003 | V6H003 | X2H027 |
| B1H001 | C7H003 | G4H006 | H9H004 | P4H001 | T5H004 | V6H004 | X2H028 |
| B1H002 | C8H003 | G4H008 | H9H005 | Q1H001 | U1H006 | V6H006 | X2H031 |
| B1H004 | C8H012 | G4H009 | J1H015 | Q3H004 | U2H001 | V7H012 | X3H001 |
| B2H001 | D1H003 | G4H010 | J2H005 | Q9H002 | U2H006 | V7H016 | X3H002 |
| B4H005 | D1H009 | G4H012 | J2H006 | Q9H019 | U2H007 | V7H017 | X3H003 |
| B5H002 | D2H001 | G4H013 | J2H007 | R1H001 | U2H011 | W1H004 | X3H006 |
| B6H001 | D3H003 | G4H014 | J3H013 | R1H005 | U2H012 | W3H014 | X3H007 |

**Appendix 1.2** : Department of Agricultural Engineering, University of Natal, Pietermaritzburg, gauging weir utilised

| |
|---|
| U2H018 |

**Appendix 2.7** : Summary of the proportions of each geology comprising each of the catchments

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| A30H001 | 6 | Vp | 4 | 2 | 390.0 | 33.2 | 50 | 8.3 |
| A30H001 | 10 | Vm | 1 | 2 | 784.1 | 66.8 | 50 | 66.8 |
| | | | | | | | | |
| A40H002 | 3 | Mw | 1 | 3 | 1529.8 | 85.1 | 50 | 127.6 |
| A40H002 | 13 | Vro | 1 | 2 | 218.0 | 12.1 | 10 | 2.4 |
| A40H002 | 15 | VMrl | 1 | 1 | 50.0 | 2.8 | 5 | 0.1 |
| | | | | | | | | |
| A40H005 | 3 | Mw | 1 | 3 | 3537.4 | 93.0 | 50 | 139.4 |
| A40H005 | 13 | Vro | 1 | 2 | 218.0 | 5.7 | 10 | 1.1 |
| A40H005 | 15 | VMrl | 1 | 1 | 50.0 | 1.3 | 5 | 0.1 |
| | | | | | | | | |
| A40H008 | 3 | Mw | 1 | 3 | 497.7 | 100.0 | 50 | 150.0 |
| | | | | | | | | |
| A50H004 | 3 | Mw | 1 | 3 | 637.5 | 100.0 | 50 | 150.0 |
| | | | | | | | | |
| A60H011 | 3 | Mw | 1 | 3 | 73.6 | 100.0 | 50 | 150.0 |
| | | | | | | | | |
| A60H012 | 3 | Mw | 1 | 3 | 46.4 | 38.8 | 50 | 58.2 |
| A60H012 | 13 | Vro | 1 | 2 | 73.2 | 61.2 | 10 | 12.2 |
| | | | | | | | | |
| A90H002 | 11 | Ms | 1 | 1 | 106.9 | 100.0 | 50 | 50.0 |
| | | | | | | | | |
| A90H003 | 11 | Ms | 1 | 1 | 62.0 | 100.0 | 50 | 50.0 |
| | | | | | | | | |
| A90H004 | 11 | Ms | 1 | 1 | 331.4 | 100.0 | 50 | 50.0 |
| | | | | | | | | |
| B10H001 | 3 | VMlw | 1 | 1 | 53.7 | 1.4 | 30 | 0.4 |
| B10H001 | 5 | Pes | 1 | 1 | 3487.9 | 94.0 | 50 | 47.0 |
| B10H001 | 6 | VMlw | 1 | 1 | 43.4 | 1.2 | 30 | 0.4 |
| B10H001 | 9 | CPd | 1 | 1 | 11.0 | 0.3 | 30 | 0.1 |
| B10H001 | 13 | Vro | 1 | 2 | 115.1 | 3.1 | 10 | 0.6 |
| | | | | | | | | |
| B10H002 | 3 | VMlw | 1 | 1 | 5.1 | 2.1 | 30 | 0.6 |
| B10H002 | 5 | Pes | 1 | 1 | 175.2 | 71.5 | 50 | 35.7 |
| B10H002 | 9 | CPd | 1 | 1 | 64.8 | 26.5 | 30 | 7.9 |
| | | | | | | | | |
| B10H004 | 3 | VMlw | 1 | 1 | 186.4 | 49.1 | 30 | 14.7 |
| B10H004 | 5 | Pes | 1 | 1 | 182.5 | 48.0 | 50 | 24.0 |
| B10H004 | 13 | Vro | 1 | 2 | 11.0 | 2.9 | 10 | 0.6 |
| | | | | | | | | |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area ($km^2$) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| B20H001 | 3 | VMlw | 1 | 1 | 89.9 | 5.6 | 30 | 1.7 |
| B20H001 | 5 | Pes | 1 | 1 | 415.1 | 26.0 | 50 | 13.0 |
| B20H001 | 6 | Vp | 4 | 2 | 882.3 | 55.2 | 50 | 13.8 |
| B20H001 | 10 | Vm | 1 | 2 | 209.8 | 13.1 | 50 | 13.1 |
| | | | | | | | | |
| B40H005 | 6 | Vp | 1 | 2 | 191.5 | 100.0 | 50 | 100.0 |
| | | | | | | | | |
| B50H002 | 3 | VMlw | 1 | 1 | 3287.7 | 10.4 | 30 | 3.1 |
| B50H002 | 5 | Pes | 1 | 1 | 7040.4 | 22.3 | 50 | 11.1 |
| B50H002 | 5 | Pe | 1 | 1 | 289.0 | 0.9 | 10 | 0.1 |
| B50H002 | 5 | PTru | 1 | 1 | 2549.0 | 8.1 | 30 | 2.4 |
| B50H002 | 6 | Vt | 4 | 3 | 374.9 | 1.2 | 30 | 0.3 |
| B50H002 | 6 | VMlw | 1 | 1 | 43.4 | 0.1 | 30 | 0.0 |
| B50H002 | 6 | Vrw | 1 | 1 | 76.1 | 0.2 | 50 | 0.1 |
| B50H002 | 6 | Vp | 1 | 2 | 46.3 | 0.1 | 50 | 0.1 |
| B50H002 | 6 | Vp | 4 | 2 | 1750.8 | 5.5 | 50 | 1.4 |
| B50H002 | 9 | CPd | 1 | 1 | 456.2 | 1.4 | 30 | 0.4 |
| B50H002 | 10 | Vm | 4 | 2 | 73.3 | 0.2 | 50 | 0.1 |
| B50H002 | 10 | Vm | 1 | 2 | 401.3 | 1.3 | 50 | 1.3 |
| B50H002 | 11 | Zp | 4 | 3 | 85.1 | 0.3 | 5 | 0.0 |
| B50H002 | 11 | Vgwb | 4 | 2 | 154.4 | 0.5 | 10 | 0.0 |
| B50H002 | 11 | Vg | 4 | 3 | 275.5 | 0.9 | 5 | 0.0 |
| B50H002 | 13 | Vro | 1 | 2 | 2636.4 | 8.3 | 10 | 1.7 |
| B50H002 | 14 | Jl | 1 | 1 | 2735.5 | 8.7 | 5 | 0.4 |
| B50H002 | 15 | VMrl | 1 | 1 | 6466.7 | 20.5 | 5 | 1.0 |
| B50H002 | 15 | V | 3 | 1 | 216.9 | 0.7 | 5 | 0.0 |
| B50H002 | 15 | RV | 3 | 1 | 393.2 | 1.2 | 5 | 0.0 |
| B50H002 | 16 | Vru | 1 | 1 | 2263.9 | 7.2 | 5 | 0.4 |
| | | | | | | | | |
| B60H001 | 6 | Vp | 1 | 2 | 136.5 | 26.5 | 50 | 26.5 |
| B60H001 | 10 | Vm | 1 | 2 | 311.1 | 60.3 | 50 | 60.3 |
| B60H001 | 11 | Vgwb | 4 | 2 | 60.6 | 11.7 | 10 | 0.6 |
| B60H001 | 15 | Z | 4 | 2 | 7.7 | 1.5 | 5 | 0.0 |
| | | | | | | | | |
| B60H002 | 10 | Vm | 1 | 2 | 16.7 | 16.4 | 50 | 16.4 |
| B60H002 | 11 | Vgwb | 4 | 2 | 77.2 | 75.7 | 10 | 3.8 |
| B60H002 | 15 | Z | 4 | 2 | 8.1 | 7.9 | 5 | 0.2 |
| | | | | | | | | |
| B60H003 | 10 | Vm | 1 | 2 | 16.7 | 17.6 | 50 | 17.6 |
| B60H003 | 11 | Vgwb | 4 | 2 | 70.1 | 73.8 | 10 | 3.7 |
| B60H003 | 15 | Z | 4 | 2 | 8.1 | 8.5 | 5 | 0.2 |
| | | | | | | | | |
| B70H004 | 11 | Vgwb | 4 | 2 | 9.3 | 6.8 | 10 | 0.3 |
| B70H004 | 15 | Z | 4 | 2 | 127.0 | 93.2 | 5 | 2.3 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| B70H008 | 10 | Vm | 1 | 2 | 7.2 | 0.9 | 50 | 0.9 |
| B70H008 | 11 | Vgwb | 4 | 2 | 147.6 | 17.6 | 10 | 0.9 |
| B70H008 | 11 | Zg | 4 | 3 | 101.4 | 12.1 | 10 | 0.9 |
| B70H008 | 15 | Z | 4 | 2 | 584.4 | 69.5 | 5 | 1.7 |
| | | | | | | | | |
| B70H010 | 11 | Zg | 4 | 3 | 29.8 | 9.3 | 10 | 0.7 |
| B70H010 | 11 | Vgwb | 4 | 2 | 88.0 | 27.3 | 10 | 1.4 |
| B70H010 | 15 | Z | 4 | 2 | 204.2 | 63.4 | 5 | 1.6 |
| | | | | | | | | |
| C11H007 | 4 | Pe | 1 | 1 | 774.8 | 16.3 | 10 | 1.6 |
| C11H007 | 5 | Pes | 1 | 1 | 3973.4 | 83.7 | 50 | 41.8 |
| | | | | | | | | |
| C30H003 | 5 | Pes | 1 | 1 | 255.6 | 2.3 | 50 | 1.2 |
| C30H003 | 6 | RVv | 3 | 1 | 467.4 | 4.2 | 15 | 0.2 |
| C30H003 | 9 | CPd | 1 | 1 | 37.3 | 0.3 | 30 | 0.1 |
| C30H003 | 10 | Vm | 1 | 2 | 1082.5 | 9.8 | 50 | 9.8 |
| C30H003 | 11 | Rdw | 4 | 2 | 280.3 | 2.5 | 15 | 0.2 |
| C30H003 | 11 | RVv | 3 | 1 | 7450.7 | 67.7 | 15 | 3.4 |
| C30H003 | 11 | Zk | 4 | 3 | 96.9 | 0.9 | 5 | 0.0 |
| C30H003 | 15 | Z | 3 | 2 | 1236.8 | 11.2 | 5 | 0.4 |
| C30H003 | 15 | RV | 1 | 1 | 93.1 | 0.8 | 5 | 0.0 |
| | | | | | | | | |
| C51H012 | 5 | Trt | 1 | 1 | 519.0 | 21.9 | 10 | 2.2 |
| C51H012 | 5 | Pa | 1 | 2 | 1848.1 | 78.1 | 15 | 23.4 |
| | | | | | | | | |
| C60H003 | 4 | Pe | 1 | 1 | 1299.3 | 16.7 | 10 | 1.7 |
| C60H003 | 5 | Pes | 1 | 1 | 1113.1 | 14.3 | 50 | 7.2 |
| C60H003 | 5 | TRmc | 1 | 1 | 380.8 | 4.9 | 30 | 1.5 |
| C60H003 | 5 | Trt | 1 | 1 | 1198.3 | 15.4 | 10 | 1.5 |
| C60H003 | 5 | Pa | 1 | 2 | 3782.6 | 48.7 | 15 | 14.6 |
| | | | | | | | | |
| C80H003 | 5 | Pa | 1 | 2 | 864.2 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| C80H012 | 5 | Trt | 1 | 1 | 217.8 | 55.7 | 10 | 5.6 |
| C80H012 | 5 | Pa | 1 | 2 | 173.1 | 44.3 | 15 | 13.3 |
| | | | | | | | | |
| E10H016 | 3 | OSt | 2 | 3 | 163.4 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| E20H002 | 3 | OSt | 2 | 3 | 1268.4 | 18.3 | 15 | 4.1 |
| E20H002 | 3 | Dw | 2 | 3 | 2612.2 | 37.7 | 15 | 8.5 |
| E20H002 | 4 | Pe | 1 | 1 | 842.0 | 12.2 | 10 | 1.2 |
| E20H002 | 4 | Db | 2 | 3 | 592.0 | 8.5 | 20 | 2.6 |
| E20H002 | 5 | Pe | 1 | 1 | 318.6 | 4.6 | 10 | 0.5 |
| E20H002 | 5 | Pa | 1 | 2 | 262.9 | 3.8 | 15 | 1.1 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| E20H002 | 7 | CPde | 2 | 2 | 311.7 | 4.5 | 20 | 0.9 |
| E20H002 | 9 | CPd | 1 | 1 | 718.9 | 10.4 | 30 | 3.1 |
| | | | | | | | | |
| G10H003 | 3 | OSt | 2 | 3 | 27.5 | 58.8 | 15 | 13.2 |
| G10H003 | 6 | Nm | 4 | 3 | 19.2 | 41.2 | 15 | 4.6 |
| G10H007 | 3 | OSt | 2 | 3 | 293.5 | 40.3 | 15 | 9.1 |
| G10H007 | 6 | Nm | 4 | 3 | 268.8 | 36.9 | 15 | 4.1 |
| G10H007 | 15 | N-C | 3 | 1 | 166.7 | 22.9 | 5 | 0.4 |
| | | | | | | | | |
| G10H011 | 3 | OSt | 2 | 3 | 27.1 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| G20H008 | 3 | OSt | 2 | 3 | 19.8 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| G20H012 | 6 | Nm | 4 | 3 | 171.6 | 69.7 | 15 | 7.8 |
| G20H012 | 15 | N-C | 1 | 1 | 74.6 | 30.3 | 5 | 1.5 |
| | | | | | | | | |
| G30H001 | 3 | OSt | 2 | 3 | 50.6 | 7.6 | 15 | 1.7 |
| G30H001 | 6 | Nm | 4 | 3 | 613.2 | 92.4 | 15 | 10.4 |
| | | | | | | | | |
| G40H006 | 3 | OSt | 4 | 3 | 152.3 | 25.3 | 15 | 2.8 |
| G40H006 | 4 | Db | 4 | 3 | 405.8 | 67.5 | 20 | 10.1 |
| G40H006 | 4 | Db | 2 | 3 | 43.3 | 7.2 | 20 | 2.2 |
| | | | | | | | | |
| G40H014 | 3 | OSt | 2 | 3 | 133.6 | 54.2 | 15 | 12.2 |
| G40H014 | 4 | Db | 4 | 3 | 112.9 | 45.8 | 20 | 6.9 |
| | | | | | | | | |
| G50H008 | 4 | Db | 4 | 3 | 382.2 | 100.0 | 20 | 15.0 |
| | | | | | | | | |
| H10H007 | 3 | OSt | 2 | 3 | 82.4 | 97.4 | 15 | 21.9 |
| H10H007 | 6 | Nm | 4 | 3 | 2.2 | 2.6 | 15 | 0.3 |
| | | | | | | | | |
| H10H013 | 3 | OSt | 2 | 3 | 52.1 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| H10H017 | 3 | OSt | 2 | 3 | 54.9 | 90.6 | 15 | 20.4 |
| H10H017 | 15 | N-C | 3 | 1 | 5.7 | 9.4 | 5 | 0.2 |
| | | | | | | | | |
| H10H018 | 3 | OSt | 2 | 3 | 78.6 | 71.0 | 15 | 16.0 |
| H10H018 | 15 | N-C | 3 | 1 | 32.0 | 29.0 | 5 | 0.5 |
| | | | | | | | | |
| H20H001 | 3 | OSt | 2 | 3 | 492.3 | 70.1 | 15 | 15.8 |
| H20H001 | 4 | Db | 2 | 3 | 210.4 | 29.9 | 20 | 9.0 |
| | | | | | | | | |
| H20H003 | 3 | OSt | 2 | 3 | 496.8 | 68.7 | 15 | 15.5 |
| H20H003 | 4 | Db | 2 | 3 | 210.4 | 29.1 | 20 | 8.7 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| H20H003 | 6 | Nm | 4 | 3 | 15.9 | 2.2 | 15 | 0.2 |
| | | | | | | | | |
| H20H005 | 3 | OSt | 2 | 3 | 16.0 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| H40H005 | 3 | OSt | 2 | 3 | 15.1 | 63.4 | 15 | 14.3 |
| H40H005 | 6 | Nm | 4 | 3 | 8.7 | 36.6 | 15 | 4.1 |
| | | | | | | | | |
| H60H008 | 3 | OSt | 2 | 3 | 38.9 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| H70H003 | 2 | Je | 1 | 1 | 27.7 | 6.0 | 50 | 3.0 |
| H70H003 | 3 | OSt | 2 | 3 | 167.4 | 36.4 | 15 | 8.2 |
| H70H003 | 4 | Db | 4 | 3 | 45.0 | 9.8 | 20 | 1.5 |
| H70H003 | 4 | Db | 2 | 3 | 219.5 | 47.8 | 20 | 14.3 |
| | | | | | | | | |
| H90H004 | 3 | OSt | 2 | 3 | 50.0 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| H90H005 | 2 | Je | 1 | 1 | 70.8 | 30.9 | 50 | 15.4 |
| H90H005 | 3 | OSt | 2 | 3 | 124.4 | 54.3 | 15 | 12.2 |
| H90H005 | 4 | Db | 4 | 3 | 34.0 | 14.8 | 20 | 2.2 |
| | | | | | | | | |
| J25H005 | 3 | Dw | 2 | 3 | 5.5 | 2.1 | 15 | 0.5 |
| J25H005 | 3 | OSt | 2 | 3 | 175.9 | 65.8 | 15 | 14.8 |
| J25H005 | 4 | Db | 2 | 3 | 79.7 | 29.8 | 20 | 8.9 |
| J25H005 | 6 | Nk | 4 | 3 | 6.1 | 2.3 | 30 | 0.5 |
| | | | | | | | | |
| J35H013 | 3 | OSt | 2 | 3 | 27.9 | 94.9 | 15 | 21.3 |
| J35H013 | 6 | Nk | 4 | 3 | 1.5 | 5.1 | 30 | 1.2 |
| | | | | | | | | |
| J35H017 | 3 | OSt | 2 | 3 | 158.3 | 45.5 | 15 | 10.2 |
| J35H017 | 4 | Db | 2 | 3 | 189.5 | 54.5 | 20 | 16.3 |
| | | | | | | | | |
| J40H003 | 3 | OSt | 2 | 3 | 58.7 | 61.6 | 15 | 13.9 |
| J40H003 | 4 | Db | 4 | 3 | 36.5 | 38.4 | 20 | 5.8 |
| | | | | | | | | |
| J40H004 | 3 | OSt | 2 | 3 | 92.3 | 92.9 | 15 | 20.9 |
| J40H004 | 6 | Nka | 4 | 3 | 7.0 | 7.1 | 10 | 0.5 |
| | | | | | | | | |
| K30H004 | 3 | OSt | 2 | 3 | 30.1 | 89.0 | 15 | 20.0 |
| K30H004 | 6 | Nka | 4 | 3 | 3.7 | 11.0 | 10 | 0.8 |
| | | | | | | | | |
| K30H005 | 3 | OSt | 2 | 3 | 77.2 | 98.0 | 15 | 22.1 |
| K30H005 | 6 | Nka | 4 | 3 | 1.6 | 2.0 | 10 | 0.1 |
| | | | | | | | | |
| | | | | | | | | |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km$^2$) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| K40H001 | 3 | OSt | 2 | 3 | 70.4 | 63.1 | 15 | 14.2 |
| K40H001 | 6 | Nka | 4 | 3 | 28.2 | 25.3 | 10 | 1.9 |
| K40H001 | 15 | N-C | 3 | 1 | 13.0 | 11.7 | 5 | 0.2 |
| | | | | | | | | |
| K40H002 | 3 | OSt | 2 | 3 | 22.9 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| K40H003 | 3 | OSt | 2 | 3 | 71.7 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| K50H002 | 3 | OSt | 2 | 3 | 134.4 | 100.0 | 15 | 22.5 |
| K60H001 | 3 | OSt | 2 | 3 | 161.6 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| K70H001 | 3 | OSt | 2 | 3 | 55.7 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| K80H001 | 3 | OSt | 2 | 3 | 25.6 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| L82H001 | 3 | OSt | 2 | 3 | 20.7 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| L82H002 | 3 | OSt | 2 | 3 | 52.3 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| P40H001 | 3 | Dw | 2 | 3 | 576.3 | 100.0 | 15 | 22.5 |
| | | | | | | | | |
| Q92H002 | 5 | Trt | 1 | 1 | 231.4 | 18.5 | 10 | 1.9 |
| Q92H002 | 5 | Pa | 1 | 2 | 1018.2 | 81.5 | 15 | 24.4 |
| | | | | | | | | |
| Q94H019 | 5 | Pa | 1 | 2 | 64.5 | 84.4 | 15 | 25.3 |
| Q94H019 | 5 | Trt | 1 | 1 | 12.0 | 15.6 | 10 | 1.6 |
| | | | | | | | | |
| R10H001 | 5 | Pa | 1 | 2 | 233.7 | 97.4 | 15 | 29.2 |
| R10H001 | 5 | Trt | 1 | 1 | 6.1 | 2.6 | 10 | 0.3 |
| | | | | | | | | |
| R10H005 | 5 | Trt | 1 | 1 | 42.1 | 8.7 | 10 | 0.9 |
| R10H005 | 5 | Pa | 1 | 2 | 443.8 | 91.3 | 15 | 27.4 |
| | | | | | | | | |
| R10H006 | 5 | Pa | 1 | 2 | 99.8 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| R10H014 | 5 | Trt | 1 | 1 | 6.1 | 8.6 | 10 | 0.9 |
| R10H014 | 5 | Pa | 1 | 2 | 64.7 | 91.4 | 15 | 27.4 |
| | | | | | | | | |
| R20H001 | 5 | Pa | 1 | 2 | 28.6 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| R20H005 | 5 | Pa | 1 | 2 | 406.5 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| R20H006 | 5 | Pa | 1 | 2 | 112.0 | 100.0 | 15 | 30.0 |
| | | | | | | | | |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km$^2$) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| R20H008 | 5 | Pa | 1 | 2 | 62.1 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| S30H006 | 5 | Trt | 1 | 1 | 1612.9 | 73.7 | 10 | 7.4 |
| S30H006 | 5 | Trmc | 1 | 1 | 574.6 | 26.3 | 30 | 7.9 |
| | | | | | | | | |
| S60H003 | 5 | Trt | 1 | 1 | 182.4 | 84.4 | 10 | 8.3 |
| S60H003 | 5 | Pa | 1 | 2 | 33.7 | 15.6 | 15 | 4.7 |
| | | | | | | | | |
| T10H004 | 5 | Trmc | 1 | 1 | 1400.3 | 28.4 | 30 | 8.5 |
| T10H004 | 5 | Trt | 1 | 1 | 3528.3 | 71.6 | 10 | 7.2 |
| | | | | | | | | |
| T20H002 | 5 | Trt | 1 | 1 | 1175.4 | 97.2 | 10 | 9.7 |
| T20H002 | 5 | Trmc | 1 | 1 | 20.4 | 1.7 | 30 | 0.5 |
| T20H002 | 5 | Pa | 1 | 2 | 13.4 | 1.1 | 15 | 0.3 |
| | | | | | | | | |
| T30H004 | 5 | Pa | 1 | 2 | 901.4 | 87.5 | 15 | 26.2 |
| T30H004 | 5 | Trt | 1 | 1 | 129.2 | 12.5 | 10 | 1.3 |
| | | | | | | | | |
| T30H008 | 5 | Pa | 1 | 2 | 186.1 | 7.6 | 15 | 2.3 |
| T30H008 | 5 | Trt | 1 | 1 | 2032.4 | 82.7 | 10 | 8.3 |
| T30H008 | 5 | Trmc | 1 | 1 | 239.1 | 9.7 | 30 | 2.9 |
| | | | | | | | | |
| T30H009 | 5 | Trmc | 1 | 1 | 280.4 | 91.4 | 30 | 27.4 |
| T30H009 | 14 | Jdr | 1 | 1 | 26.4 | 8.6 | 5 | 0.4 |
| | | | | | | | | |
| T40H001 | 4 | Pe | 1 | 1 | 699.3 | 96.3 | 10 | 9.6 |
| T40H001 | 5 | Pa | 1 | 2 | 27.2 | 3.7 | 15 | 1.1 |
| | | | | | | | | |
| T50H002 | 4 | Pe | 1 | 1 | 656.5 | 75.1 | 10 | 7.5 |
| T50H002 | 5 | Pa | 1 | 2 | 218.0 | 24.9 | 15 | 7.5 |
| | | | | | | | | |
| T50H003 | 5 | Trt | 1 | 1 | 126.7 | 90.5 | 10 | 9.0 |
| T50H003 | 14 | Jdr | 1 | 1 | 13.3 | 9.5 | 5 | 0.5 |
| | | | | | | | | |
| T50H004 | 5 | Trt | 1 | 1 | 463.2 | 88.3 | 10 | 8.8 |
| T50H004 | 14 | Jdr | 1 | 1 | 61.6 | 11.7 | 5 | 0.6 |
| | | | | | | | | |
| U10H006 | 4 | Pe | 1 | 1 | 1145.8 | 26.4 | 10 | 2.6 |
| U10H006 | 5 | Trt | 1 | 1 | 1164.8 | 26.8 | 10 | 2.7 |
| U10H006 | 5 | Pa | 1 | 2 | 1040.4 | 23.9 | 15 | 7.2 |
| U10H006 | 5 | OSn | 1 | 1 | 88.1 | 2.0 | 10 | 0.2 |
| U10H006 | 9 | CPd | 1 | 1 | 350.7 | 8.1 | 30 | 2.4 |
| U10H006 | 12 | Nmp | 4 | 3 | 325.4 | 7.5 | 5 | 0.3 |
| U10H006 | 14 | Jdr | 1 | 1 | 230.5 | 5.3 | 5 | 0.3 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| U20H001 | 4 | Pe | 1 | 1 | 376.6 | 39.5 | 10 | 4.0 |
| U20H001 | 5 | Trt | 1 | 1 | 119.9 | 12.6 | 10 | 1.3 |
| U20H001 | 5 | Pa | 1 | 2 | 456.0 | 47.9 | 15 | 14.4 |
| | | | | | | | | |
| U20H006 | 4 | Pe | 1 | 1 | 219.1 | 64.4 | 10 | 6.4 |
| U20H006 | 5 | Pa | 1 | 2 | 121.3 | 35.6 | 15 | 10.7 |
| | | | | | | | | |
| U20H007 | 4 | Pe | 1 | 1 | 100.8 | 28.4 | 10 | 2.8 |
| U20H007 | 5 | Trt | 1 | 1 | 6.4 | 1.8 | 10 | 0.2 |
| U20H007 | 5 | Pa | 1 | 2 | 247.5 | 69.8 | 15 | 20.9 |
| U20H011 | 4 | Pe | 1 | 1 | 171.3 | 96.4 | 10 | 9.6 |
| U20H011 | 5 | Pa | 1 | 2 | 6.4 | 3.6 | 15 | 1.1 |
| | | | | | | | | |
| U20H012 | 4 | Pe | 1 | 1 | 159.6 | 36.4 | 10 | 3.6 |
| U20H012 | 5 | Pes | 1 | 1 | 12.3 | 2.8 | 50 | 1.4 |
| U20H012 | 5 | OSn | 1 | 1 | 136.5 | 31.2 | 10 | 3.1 |
| U20H012 | 8 | CPde | 1 | 2 | 44.0 | 10.0 | 20 | 4.0 |
| | | | | | | | | |
| U20H012 | 9 | CPd | 1 | 1 | 85.4 | 19.5 | 30 | 5.9 |
| | | | | | | | | |
| U20H013 | 4 | Pe | 1 | 1 | 26.1 | 8.8 | 10 | 0.9 |
| U20H013 | 5 | Trt | 1 | 1 | 113.5 | 38.4 | 10 | 3.8 |
| U20H013 | 5 | Pa | 1 | 2 | 155.9 | 52.8 | 15 | 15.8 |
| | | | | | | | | |
| U30H002 | 5 | OSn | 1 | 1 | 140.6 | 39.1 | 10 | 3.9 |
| U30H002 | 7 | CPde | 1 | 1 | 11.1 | 3.1 | 20 | 0.6 |
| U30H002 | 12 | Nmp | 4 | 1 | 207.8 | 57.8 | 5 | 0.7 |
| | | | | | | | | |
| U40H002 | 4 | Pe | 1 | 1 | 52.8 | 16.6 | 10 | 1.7 |
| U40H002 | 5 | Pes | 1 | 1 | 77.3 | 24.3 | 50 | 12.1 |
| U40H002 | 8 | CPde | 1 | 1 | 188.4 | 59.1 | 20 | 11.8 |
| | | | | | | | | |
| U70H007 | 4 | Pe | 1 | 1 | 99.2 | 100.0 | 10 | 10.0 |
| | | | | | | | | |
| V10H001 | 4 | Pe | 1 | 1 | 13.5 | 0.3 | 10 | 0.0 |
| V10H001 | 5 | Trt | 1 | 1 | 1000.4 | 23.9 | 10 | 2.4 |
| V10H001 | 5 | TRmc | 1 | 1 | 6.7 | 0.2 | 30 | 0.0 |
| V10H001 | 5 | Pa | 1 | 2 | 2651.9 | 63.3 | 15 | 19.0 |
| V10H001 | 14 | Jdr | 1 | 1 | 516.0 | 12.3 | 5 | 0.6 |
| | | | | | | | | |
| V10H002 | 5 | Pa | 1 | 2 | 591.3 | 34.6 | 15 | 10.4 |
| V10H002 | 5 | TRmc | 1 | 1 | 6.7 | 0.4 | 30 | 0.1 |
| V10H002 | 5 | Trt | 1 | 1 | 721.2 | 42.2 | 10 | 4.2 |
| V10H002 | 14 | Jdr | 1 | 1 | 391.5 | 22.9 | 5 | 1.1 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| V10H009 | 5 | Trt | 1 | 1 | 56.0 | 28.6 | 10 | 2.9 |
| V10H009 | 5 | Pa | 1 | 2 | 139.9 | 71.4 | 15 | 21.4 |
| | | | | | | | | |
| V10H031 | 5 | Pa | 1 | 2 | 161.3 | 100.0 | 15 | 30.0 |
| | | | | | | | | |
| V10H038 | 4 | Pe | 1 | 1 | 941.5 | 56.8 | 10 | 5.7 |
| V10H038 | 5 | Pa | 1 | 2 | 674.0 | 40.7 | 15 | 12.2 |
| V10H038 | 5 | Trt | 1 | 1 | 40.9 | 2.5 | 10 | 0.2 |
| | | | | | | | | |
| | | | | | | | | |
| V20H001 | 4 | Pe | 1 | 1 | 323.9 | 16.9 | 10 | 1.7 |
| V20H001 | 5 | Pa | 1 | 2 | 896.5 | 46.8 | 15 | 14.1 |
| V20H001 | 5 | Pes | 1 | 1 | 46.2 | 2.4 | 50 | 1.2 |
| V20H001 | 5 | Trt | 1 | 1 | 545.7 | 28.5 | 10 | 2.9 |
| V20H001 | 14 | Jdr | 1 | 1 | 101.3 | 5.3 | 5 | 0.3 |
| | | | | | | | | |
| V20H005 | 5 | Trt | 1 | 1 | 169.9 | 63.4 | 10 | 6.3 |
| V20H005 | 5 | Pa | 1 | 2 | 25.8 | 9.6 | 15 | 2.9 |
| V20H005 | 14 | Jdr | 1 | 1 | 72.4 | 27.0 | 5 | 1.3 |
| | | | | | | | | |
| V30H002 | 4 | Pe | 1 | 1 | 763.5 | 49.8 | 10 | 5.0 |
| V30H002 | 5 | Pes | 1 | 1 | 263.7 | 17.2 | 50 | 8.6 |
| V30H002 | 5 | Pa | 1 | 2 | 505.8 | 33.0 | 15 | 9.9 |
| | | | | | | | | |
| V30H003 | 4 | Pe | 1 | 1 | 521.9 | 60.8 | 10 | 6.1 |
| V30H003 | 5 | Pa | 1 | 2 | 53.1 | 6.2 | 15 | 1.9 |
| V30H003 | 5 | Pes | 1 | 1 | 283.2 | 33.0 | 50 | 16.5 |
| | | | | | | | | |
| V30H005 | 4 | Pe | 1 | 1 | 304.2 | 44.6 | 10 | 4.5 |
| V30H005 | 5 | Pa | 1 | 2 | 377.3 | 55.4 | 15 | 16.6 |
| | | | | | | | | |
| V30H007 | 4 | Pe | 1 | 1 | 44.7 | 34.5 | 10 | 3.5 |
| V30H007 | 5 | Pa | 1 | 2 | 57.6 | 44.5 | 15 | 13.4 |
| V30H007 | 5 | Pes | 1 | 1 | 27.0 | 20.9 | 50 | 10.5 |
| | | | | | | | | |
| V30H009 | 4 | Pe | 1 | 1 | 96.9 | 64.4 | 10 | 6.4 |
| V30H009 | 5 | Pes | 1 | 1 | 53.6 | 35.6 | 50 | 17.8 |
| | | | | | | | | |
| V60H003 | 4 | Pe | 1 | 1 | 131.4 | 42.4 | 10 | 4.2 |
| V60H003 | 5 | Pes | 1 | 1 | 178.4 | 57.6 | 50 | 28.8 |
| | | | | | | | | |
| V60H004 | 4 | Pe | 1 | 1 | 224.1 | 33.8 | 10 | 3.4 |
| V60H004 | 5 | Pa | 1 | 2 | 57.8 | 8.7 | 15 | 2.6 |
| V60H004 | 5 | Pes | 1 | 1 | 380.3 | 57.4 | 50 | 28.7 |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| V60H006 | 4 | Pe | 1 | 1 | 44.1 | 41.0 | 10 | 4.1 |
| V60H006 | 5 | Pes | 1 | 1 | 5.5 | 5.1 | 50 | 2.6 |
| V60H006 | 5 | Pa | 1 | 2 | 57.8 | 53.8 | 15 | 16.1 |
| | | | | | | | | |
| V70H012 | 5 | Trt | 1 | 1 | 114.8 | 57.5 | 10 | 5.7 |
| V70H012 | 5 | Pa | 1 | 2 | 84.9 | 42.5 | 15 | 12.8 |
| | | | | | | | | |
| V70H016 | 5 | Trt | 1 | 1 | 84.2 | 68.9 | 10 | 6.9 |
| V70H016 | 14 | Jdr | 1 | 1 | 38.0 | 31.1 | 5 | 1.6 |
| | | | | | | | | |
| | | | | | | | | |
| V70H017 | 5 | Trt | 1 | 1 | 134.8 | 48.3 | 10 | 4.8 |
| V70H017 | 14 | Jdr | 1 | 1 | 144.3 | 51.7 | 5 | 2.6 |
| | | | | | | | | |
| W41H004 | 4 | Pe | 1 | 1 | 17.5 | 1.8 | 10 | 0.2 |
| W41H004 | 5 | Pa | 1 | 2 | 22.8 | 2.4 | 15 | 0.7 |
| W41H004 | 5 | Pes | 1 | 1 | 772.6 | 80.9 | 50 | 40.5 |
| W41H004 | 8 | CPde | 1 | 2 | 37.7 | 3.9 | 20 | 1.6 |
| W41H004 | 15 | Z | 4 | 2 | 104.1 | 10.9 | 5 | 0.3 |
| | | | | | | | | |
| W51H006 | 5 | Pes | 1 | 1 | 155.4 | 84.4 | 50 | 42.2 |
| W51H006 | 15 | Z | 4 | 2 | 28.7 | 15.6 | 5 | 0.4 |
| | | | | | | | | |
| W53H004 | 5 | Pes | 1 | 1 | 309.2 | 66.5 | 50 | 33.3 |
| W53H004 | 15 | Z | 4 | 2 | 155.5 | 33.5 | 5 | 0.8 |
| | | | | | | | | |
| W54H008 | 5 | Pes | 1 | 1 | 7.6 | 7.1 | 50 | 3.5 |
| W54H008 | 15 | R | 3 | 2 | 100.3 | 92.9 | 5 | 3.1 |
| | | | | | | | | |
| X20H005 | 6 | Vp | 1 | 2 | 66.8 | 10.3 | 50 | 10.3 |
| X20H005 | 10 | Vm | 1 | 2 | 148.3 | 23.0 | 50 | 23.0 |
| X20H005 | 15 | Z | 4 | 2 | 430.3 | 66.7 | 5 | 1.7 |
| | | | | | | | | |
| X20H008 | 11 | Zba | 2 | 3 | 83.2 | 45.8 | 20 | 13.7 |
| X20H008 | 15 | Z | 4 | 2 | 98.5 | 54.2 | 5 | 1.4 |
| | | | | | | | | |
| X20H010 | 10 | Vm | 1 | 2 | 1.2 | 0.9 | 50 | 0.9 |
| X20H010 | 15 | Z | 4 | 2 | 126.7 | 99.1 | 5 | 2.5 |
| | | | | | | | | |
| X20H011 | 5 | Pes | 1 | 1 | 2.9 | 0.7 | 50 | 0.4 |
| X20H011 | 6 | Vp | 1 | 2 | 396.7 | 99.3 | 50 | 99.3 |
| | | | | | | | | |
| X20H012 | 6 | Vp | 1 | 2 | 93.3 | 100.0 | 50 | 100.0 |
| | | | | | | | | |

| Catchment Name | Rock Type | Lithology | Metamorphism | Deformation | Area (km²) | Proportion (%) | Baseflow Potential | Geological Index |
|---|---|---|---|---|---|---|---|---|
| X20H013 | 6 | Vp | 1 | 2 | 1475.8 | 96.6 | 50 | 96.6 |
| X20H013 | 10 | Vm | 1 | 2 | 35.8 | 2.3 | 50 | 2.3 |
| X20H013 | 15 | Z | 4 | 2 | 15.4 | 1.0 | 5 | 0.0 |
| | | | | | | | | |
| X20H014 | 6 | Vp | 1 | 2 | 229.0 | 90.4 | 50 | 90.4 |
| X20H014 | 10 | Vm | 1 | 2 | 24.2 | 9.6 | 50 | 9.6 |
| | | | | | | | | |
| X20H015 | 6 | Vp | 1 | 2 | 1210.6 | 77.8 | 50 | 77.8 |
| X20H015 | 10 | Vm | 1 | 2 | 243.8 | 15.7 | 50 | 15.7 |
| X20H015 | 15 | Z | 4 | 2 | 100.8 | 6.5 | 5 | 0.2 |
| | | | | | | | | |
| X20H022 | 11 | Zba | 2 | 3 | 782.8 | 47.3 | 20 | 14.2 |
| X20H022 | 15 | Z | 4 | 2 | 871.4 | 52.7 | 5 | 1.3 |
| | | | | | | | | |
| X20H024 | 11 | Zba | 2 | 3 | 5.9 | 7.2 | 20 | 2.2 |
| X20H024 | 15 | Z | 4 | 2 | 76.3 | 92.8 | 5 | 2.3 |
| | | | | | | | | |
| X20H027 | 6 | Vp | 1 | 2 | 78.0 | 100.0 | 50 | 100.0 |
| | | | | | | | | |
| X20H031 | 11 | Zba | 2 | 3 | 5.9 | 2.2 | 20 | 0.7 |
| X20H031 | 15 | Z | 4 | 2 | 259.7 | 97.8 | 5 | 2.4 |
| | | | | | | | | |
| X30H001 | 6 | Vp | 1 | 2 | 92.6 | 52.9 | 50 | 52.9 |
| X30H001 | 10 | Vm | 1 | 2 | 82.4 | 47.1 | 50 | 47.1 |
| | | | | | | | | |
| X30H003 | 10 | Vm | 1 | 2 | 32.7 | 62.6 | 50 | 62.6 |
| X30H003 | 11 | Vgwb | 4 | 2 | 19.6 | 37.4 | 10 | 1.9 |
| | | | | | | | | |
| X30H006 | 6 | Vp | 1 | 2 | 93.7 | 12.0 | 50 | 12.0 |
| X30H006 | 10 | Vm | 1 | 2 | 187.3 | 24.1 | 50 | 24.1 |
| X30H006 | 11 | Vgwb | 4 | 2 | 48.1 | 6.2 | 10 | 0.3 |
| X30H006 | 15 | Z | 4 | 2 | 449.0 | 57.7 | 5 | 1.4 |
| | | | | | | | | |
| X30H007 | 15 | Z | 4 | 2 | 45.4 | 100.0 | 5 | 2.5 |

## Key to the Geology

**Rock Type : Nature of the water bearing rock**

1 Porous unconsolidated to semi-consolidated sediment.
2 Consolidated porous to compact sedimentary strata.
3 Compact, dominantly arenaceous strata.
4 Compact dominantly argillaceous strata.
5 Compact argillaceous and arenaceous strata.
6 Compact sedimentary strata.
7 Mainly compact tillite, shale and sandstone (Dwyka and Ecca).

8 Mainly compact tillite and shale (Dwyka and Ecca).
9 Mainly compact tillite (Dwyka).
10 Dolomite, chert and subordinate limestone.
11 Assemblage of compact sedimentary and extrusive rocks.
12 Assemblage of compact sedimentary extrusive and intrusive rocks.
13 Acid and intermediate lavas.
14 mafic / basic lavas.
15 Acid, intermediate or alkaline intrusives.
16 Mafic / ultramafic or basic / ultrabasic intrusives.

**Lithostratigraphic unit(s) and their principal rock type(s)**

CPde Dwyka Formation and Ecca Group: Tillite with sandstone, mud, shale; intruded by dolerite along the north coast.

CPd Dwyka Formation: Tillite with subordinate sandstone, mud, shale; intruded by dolerite dykes and sheets.

Db Bokkeveld Group: Shale, siltstone, sandstone.

Dw Witteberg Group: Quartzitic sandstone, shale, diamictite.

Jdr Drakensberg Formation: Basalt.

Je Enon Formation: Conglomerate, sandstone.

Jl Letaba Formation: Basalt; N-S trending dolerite dykes along Lebombo range.

Ms Soutpansberg Group and Blouberg Formation: quartzite, conglomerate, grit, sandstone, silt, mud, shale, basalt, trachy-andesite, tuff; diabase dykes and sills.

Mw Waterberg group and Glentig Formation: Conglomerate, grit, sandstone, silt, mud, shale, trachyte; quartz porphyry; diabase dykes and sills.

NE Cape Granite Suite, Kuboos, George, Woodville Plutons: Biotite granite.

Nk Kango Group: Sandstone, shale, conglomerate, limestone.

Nka Kaaimans Group: Quartzite, phyllite, schist.

Nm Malmesbury Group; Tygerberg, Franschoek, Klipheuwel Formations; Bridgetown Complex: Schist, phyllite, phyllitic shale, shale, limestone, sandstone, greywacke, conglomerate, quartzite, greenstone.

Nmp Mapumulo Group (Mzimkulu Formation): Gneiss, granulite (marble, dolomite, granulite).

OSn Natal Group: Quartzitic sandstone, shale, arkose.

OSt Table Mountain Group: quartzitic sandstone, subordinate shale and tillite.

Pa Adelaide Subgroup: Mud, sandstone; intruded by dolerite dykes and sheets.

Pe Ecca Group: Shale; intruded by dolerite dykes and sheets.

Pes Ecca Group: shale, sandstone; intruded by dolerite dykes and sills.

PTru Undifferentiated Karoo Sequence: sandstone, silt, mud, shale; intruded by dolerite and includes patches of Letaba basalt north of the Soutpansberg.

| | |
|---|---|
| R | Houtrivier, Salisbury Kop, Mpuluzi, Gaborone, Harmony and Cunning Moor Intrusives: Biotite-muscovite granite, gneiss, leucogranite, migmatite, potassic granite, quartz monzonite, tonalite, quartz porphyry. |
| RV | Mashashane and Mashishimale Suites: Baderouke, Hugomond, Lekkersmaak, Matlala, Matok, Moletsi, Palmietfontein, Shamiriri, Shirindi, Smitskraal, Turfloop, Utrecht, Mosita and unnamed intrusives: Granite, Biotite-muscovite granite; diabase and dolerite dykes. |
| RVv | Ventersdorp Supergroup: Klipriviersberg, Zoetlief, Amalia, Hartswater and Sodium Groups; Hereford, Ritchie and Zeekoebaart formations: Andesite, quartz porphyry, dacite, rhyolite, trachyte, ignimbrite, tuff, agglomerate, volcaniclastics, conglomerate, sandstone, arkose, quartzite, shale, chert. |
| Trmc | Molteno, Clarens, Elliot Formations: sandstone, silt, mud, shale; intruded by dolerite dykes/sheets. |
| Trt | Tarkastad Subgroup: mud, sandstone; intruded by dolerite dykes and sheets. |
| V | Mpageni, Meinhardskraal and unnamed intrusives: Potassic biotite and leucocratic granites with NE trending diabase and dolerite dykes. |
| Vg | Groblersdal Group: Dennilton and Bloempoort formations: lava, tuff, schist, gneiss, slate, shale, quartzite. |
| Vgwb | Godwan Formation, Wolkberg Group and Black Reef Formation: lava, tuff, quartzite, shale, conglomerate. |
| Vm | Malmani subgroup, Assen and Black Reef formations: Dolomite, chert, subordinate quartzite, shale and conglomerate; diabase and syenite dykes and sills. |
| VMlw | Loskop and Wilge Rivier Formations: Pyroclastics, lava, quartzite, conglomerate, sandstone, silt, grit, shale, diabase dykes. |
| VMrl | Rashoop Granophyre and Lebowa Granite Suite: Granophyre, hornblende and biotite granites. |
| Vp | Pretoria Group, Duitschland, Penge and Lagrant Formations: Quartzite, shale conglomerate, iron formation, breccia, diamictite, limestone, dolomite, andesite; also includes the malmani dolomites north of the Vredefort dome; diabase sills, syenite and diabase dykes. |
| Vro | Rooiberg Group: Rhyolite, pyroclastics. |
| Vru | Rustenberg Layered Suite: Bronzitite, harzburgite, norite, pyroxenite, anorthosite, gabbro, diorite. |
| Vrw | Rust De Winter Formation: sandstone, conglomerate, rhyolite. |
| Vt | Pretoria and Chuniespoort Groups: quartzite, shale, dolomite. |
| Z | Nelspruit, Dalmein, Hebron, Halfway House, Goudplaats and unnamed intrusives: Granite, granodiorite, tonalite, gneiss, migmatite. |
| Zba | Barberton Sequence: Sandstone, shale, conglomerate, greywacke, lava, pyroclastic rocks. |
| Zg | Gravelotte Group: Ultramafic, mafic and acidic lava, tuff, schist, conglomerate, quartzite. |
| Zk | Kraaipan Group: Chert, iron formation, jaspilite, schist, lava. |
| Zp | Pietersberg Group: Ultramafic and mafic lavas, quartzite, conglomerate, chlorite schist. |

**Capitals Denote:**

| | |
|---|---|
| (a) Systems: | Q - Quaternary, T - Tertiary, K - Cretaceous, J - Jurassic, Tr - Triassic, P - Permian, C - Carboniferous, D - Devonian, O - Ordovician, S - Silurian, E - Cambrian. |
| (b) Erathems: | N - Namibian, M - Mokolian, V - Vaalian, R - Randian, Z- Swazian. |

**Degree of Metamorphism**

0 Unmetamorphosed;
1 V. low grade (burial, thermal, orogenic) characterised by minerals such as zeolite, prehnite, pumpellyite, riebeckite, minnesotaite, stilpnomelane;
2 Low grade thermal (albite - epidote hornfels facies) and burial/orogenic greenschist facies (epidote, chlorite, actinolite);
3 Medium grade thermal (hornblende hornfels) and orogenic amphibolite facies with(out) migmatite;
4 High grade thermal (pyroxene hornfels) and orogenic granulite facies;

**Degree of Deformation**

1 No deformation;
2 Moderate deformation;
3 Well deformed;

**Note:** Dykes and sheets are mentioned where they are numerous or where they are geohydrologically important. Their absence is not implied where not mentioned.

**Appendix 2.8** : Summary of the catchment areas

| Catchment | DWAF GIS Catchment Area | DWAF LHGS Catchment Area | % Difference |
|---|---|---|---|
| A30H001 | 1174 | 1165 | 0.77 |
| A40H002 | 1798 | 1777 | 1.18 |
| A40H005 | 3805 | 3786 | 0.50 |
| A40H008 | 498 | 504 | 1.19 |
| A50H004 | 637 | 629 | 1.27 |
| A60H011 | 74 | 73 | 1.37 |
| A60H012 | 120 | 120 | 0.00 |
| A90H002 | 107 | 96 | 11.46 |
| A90H003 | 62 | 62 | 0.00 |
| A90H004 | 331 | 320 | 3.44 |
| B10H001 | 3711 | 3904 | 4.94 |
| B10H002 | 247 | 252 | 1.98 |
| B10H004 | 380 | 376 | 1.06 |
| B20H001 | 1597 | 1594 | 0.19 |
| B40H005 | 191 | 188 | 1.60 |
| B50H002 | 31616 | 31416 | 0.64 |
| B60H001 | 516 | 518 | 0.39 |
| B60H002 | 102 | 97 | 5.15 |
| B60H003 | 95 | 92 | 3.26 |
| B70H004 | 136 | 136 | 0.00 |
| B70H008 | 841 | 832 | 1.08 |
| B70H010 | 322 | 318 | 1.26 |
| C11H007 | 4748 | 4686 | 1.32 |
| C30H003 | 11001 | 10990 | 0.10 |
| C51H012 | 2367 | 2372 | 0.21 |
| C60H003 | 7774 | 7765 | 0.12 |
| C80H003 | 864 | 806 | 7.20 |
| C80H012 | 393 | 386 | 1.81 |
| E10H016 | 163 | 160 | 1.88 |
| E20H002 | 6926 | 6903 | 0.33 |
| G10H003 | 47 | 46 | 2.17 |
| G10H007 | 729 | 713 | 2.24 |
| G10H011 | 27 | 27 | 0.00 |
| G20H008 | 20 | 20 | 0.00 |
| G20H012 | 246 | 244 | 0.82 |
| G30H001 | 664 | 647 | 2.63 |
| G40H006 | 601 | 600 | 0.17 |
| G40H014 | 247 | 252 | 1.98 |
| G5H008 | 382 | 382 | 0.00 |
| H10H007 | 85 | 84 | 1.19 |
| H10H013 | 52 | 53 | 1.89 |
| H10H017 | 61 | 61 | 0.00 |
| H10H018 | 111 | 113 | 1.77 |
| H20H001 | 703 | 697 | 0.86 |
| H20H003 | 723 | 718 | 0.70 |

| Catchment | DWAF GIS Catchment Area | DWAF LHGS Catchment Area | % Difference |
|---|---|---|---|
| H20H005 | 16 | 15 | 6.67 |
| H40H005 | 24 | 24 | 0.00 |
| H60H008 | 39 | 38 | 2.63 |
| H70H001 | 5532 | 9829 | 43.72 |
| H70H003 | 460 | 450 | 2.22 |
| H90H004 | 50 | 50 | 0.00 |
| H90H005 | 229 | 228 | 0.44 |
| J25H005 | 267 | 253 | 5.53 |
| J35H013 | 29 | 29 | 0.00 |
| J35H017 | 348 | 347 | 0.29 |
| J40H003 | 95 | 95 | 0.00 |
| J40H004 | 99 | 99 | 0.00 |
| K30H004 | 34 | 34 | 0.00 |
| K30H005 | 79 | 78 | 1.28 |
| K40H001 | 112 | 111 | 0.90 |
| K40H002 | 23 | 22 | 4.55 |
| K40H003 | 72 | 72 | 0.00 |
| K50H002 | 134 | 134 | 0.00 |
| K60H001 | 162 | 165 | 1.82 |
| K70H001 | 56 | 57 | 1.75 |
| K80H001 | 26 | 35 | 25.71 |
| L82H001 | 21 | 21 | 0.00 |
| L82H002 | 52 | 52 | 0.00 |
| P40H001 | 576 | 576 | 0.00 |
| Q92H002 | 1250 | 1245 | 0.40 |
| Q94H019 | 77 | 76 | 1.32 |
| R10H001 | 240 | 238 | 0.84 |
| R10H005 | 486 | 482 | 0.83 |
| R10H006 | 100 | 100 | 0.00 |
| R10H014 | 71 | 70 | 1.43 |
| R20H001 | 29 | 29 | 0.00 |
| R20H005 | 407 | 411 | 0.97 |
| R20H006 | 112 | 119 | 5.88 |
| R20H008 | 62 | 61 | 1.64 |
| S30H006 | 2188 | 2170 | 0.83 |
| S60H003 | 216 | 215 | 0.47 |
| T10H004 | 4932 | 4908 | 0.49 |
| T20H002 | 1209 | 1199 | 0.83 |
| T30H004 | 1031 | 1029 | 0.19 |
| T30H008 | 2480 | 2471 | 0.36 |
| T30H009 | 307 | 307 | 0.00 |
| T40H001 | 727 | 715 | 1.68 |
| T50H002 | 875 | 867 | 0.92 |
| T50H003 | 142 | 140 | 1.43 |
| T50H004 | 540 | 545 | 0.92 |
| U10H006 | 4373 | 4349 | 0.55 |
| U20H001 | 1914 | 1976 | 3.14 |

| Catchment | DWAF GIS Catchment Area | DWAF LHGS Catchment Area | % Difference |
|---|---|---|---|
| U20H006 | 340 | 339 | 0.30 |
| U20H007 | 355 | 358 | 0.84 |
| U20H011 | 178 | 176 | 1.14 |
| U20H012 | 438 | 438 | 0.00 |
| U20H013 | 296 | 299 | 1.00 |
| U30H002 | 360 | 356 | 1.12 |
| U40H002 | 319 | 316 | 0.95 |
| U70H007 | 99 | 114 | 13.16 |
| V10H001 | 4222 | 4176 | 1.10 |
| V10H002 | 1726 | 1689 | 2.19 |
| V10H009 | 196 | 196 | 0.00 |
| V10H031 | 161 | 162 | 0.62 |
| V10H038 | 1656 | 1644 | 0.73 |
| V20H001 | 1914 | 1976 | 3.14 |
| V20H005 | 268 | 260 | 3.08 |
| V30H002 | 1533 | 1518 | 0.99 |
| V30H003 | 858 | 850 | 0.94 |
| V30H005 | 682 | 676 | 0.89 |
| V30H007 | 129 | 129 | 0.00 |
| V30H009 | 150 | 148 | 1.35 |
| V60H003 | 310 | 312 | 0.64 |
| V60H004 | 662 | 658 | 0.61 |
| V60H006 | 107 | 109 | 1.83 |
| V70H012 | 200 | 196 | 2.04 |
| V70H016 | 122 | 121 | 0.83 |
| V70H017 | 281 | 276 | 1.81 |
| W41H004 | 956 | 948 | 0.84 |
| W51H006 | 184 | 180 | 2.22 |
| W53H004 | 465 | 460 | 1.09 |
| W54H008 | 109 | 118 | 7.63 |
| X20H005 | 645 | 642 | 0.47 |
| X20H008 | 182 | 180 | 1.11 |
| X20H010 | 128 | 126 | 1.59 |
| X20H011 | 400 | 402 | 0.50 |
| X20H012 | 93 | 91 | 2.20 |
| X20H013 | 1527 | 1518 | 0.59 |
| X20H014 | 253 | 250 | 1.20 |
| X20H015 | 1558 | 1554 | 0.26 |
| X20H022 | 1655 | 1639 | 0.98 |
| X20H024 | 82 | 80 | 2.50 |
| X20H027 | 78 | 78 | 0.00 |
| X20H031 | 266 | 262 | 1.53 |
| X30H001 | 175 | 174 | 0.57 |
| X30H003 | 52 | 52 | 0.00 |
| X30H006 | 778 | 766 | 1.57 |
| X30H007 | 45 | 46 | 2.17 |

**Appendix 2.9** : Summary of the catchment characteristics

| Catchment Name | Rainfall Seasonality | MAP (mm) | Rainfall Concentration (%) | ACRU Recharge (mm a$^{-1}$) | VEGTER Recharge (mm a$^{-1}$) | Catchment Area (km$^2$) | Average Catchment Slope (°) | Drainage Density (km/km$^2$) |
|---|---|---|---|---|---|---|---|---|
| A30H001 | 4 | 558 | 62 | 2 | 50 | 1165 | 1.7 | 0.168 |
| A40H002 | 4 | 652 | 65 | 14 | 50 | 1777 | 3.6 | 0.200 |
| A40H005 | 4 | 634 | 65 | 15 | 44 | 3786 | 3.2 | 1.693 |
| A40H008 | 4 | 672 | 64 | 23 | 34 | 504 | 4.1 | 0.223 |
| A50H004 | 4 | 628 | 65 | 15 | 58 | 629 | 4.3 | 0.290 |
| A60H011 | 3 | 639 | 64 | 3 | 45 | 73 | 3.5 | 0.307 |
| A60H012 | 4 | 630 | 64 | 1 | 45 | 120 | 4.4 | 0.199 |
| A90H002 | 4 | 1104 | 59 | 89 | 80 | 96 | 5.4 | 0.409 |
| A90H003 | 4 | 989 | 61 | 86 | 79 | 62 | 6.1 | 0.487 |
| A90H004 | 4 | 855 | 63 | 101 | 41 | 320 | 7.5 | 0.373 |
| B10H001 | 3 | 686 | 59 | 7 | 38 | 3904 | 1.4 | 0.243 |
| B10H002 | 3 | 695 | 60 | 9 | 57 | 252 | 1.1 | 0.167 |
| B10H004 | 3 | 684 | 61 | 6 | 65 | 376 | 1.4 | 0.055 |
| B20H001 | 3 | 670 | 60 | 9 | 70 | 1594 | 1.3 | 0.012 |
| B40H005 | 3 | 761 | 60 | 51 | 55 | 188 | 5.3 | 0.254 |
| B50H002 | 3 | 620 | 61 | 6 | 34 | 31416 | 2.2 | 0.025 |
| B60H001 | 4 | 1102 | 58 | 183 | 115 | 518 | 10.0 | 0.021 |
| B60H002 | 4 | 1107 | 58 | 214 | 112 | 97 | 7.6 | 0.235 |
| B60H003 | 4 | 1181 | 58 | 234 | 110 | 92 | 7.6 | 1.349 |
| B70H004 | 4 | 1049 | 59 | 117 | 79 | 136 | 7.5 | 0.184 |
| B70H008 | 4 | 708 | 63 | 51 | 64 | 832 | 3.4 | 0.153 |
| B70H010 | 4 | 777 | 63 | 70 | 89 | 318 | 4.2 | 0.275 |
| C11H007 | 3 | 708 | 58 | 22 | 45 | 4686 | 2.0 | 0.299 |
| C30H003 | 4 | 530 | 62 | 1 | 32 | 10990 | 0.6 | 0.107 |
| C51H012 | 5 | 450 | 51 | 2 | 20 | 2372 | 1.6 | 0.266 |
| C60H003 | 4 | 564 | 56 | 3 | 32 | 7765 | 1.2 | 0.070 |
| C80H003 | 3 | 666 | 58 | 14 | 45 | 806 | 2.9 | 0.356 |
| C80H012 | 4 | 610 | 56 | 6 | 39 | 386 | 1.7 | 0.294 |
| D12H009 | 4 | 675 | 51 | 16 | 2 | 24550 | 14.5 | 0.427 |
| D14H003 | 4 | 653 | 49 | 13 | 14 | 37075 | 11.7 | 0.388 |
| D20H001 | 4 | 743 | 51 | 29 | 21 | 13421 | 6.7 | 0.377 |
| D33H003 | 5 | 544 | 49 | 10 | 18 | 94765 | 6.3 | 0.304 |
| E10H016 | 2 | 480 | 58 | 146 | 41 | 160 | 16.1 | 0.312 |
| E20H002 | 2 | 312 | 50 | 54 | 26 | 6903 | 5.7 | 0.002 |
| G10H003 | 2 | 948 | 49 | 270 | 135 | 46 | 11.3 | 0.213 |
| G10H007 | 2 | 1113 | 48 | 305 | 105 | 713 | 10.4 | 0.403 |
| G10H011 | 2 | 706 | 45 | 191 | 65 | 27 | 7.1 | 0.287 |
| G20H008 | 2 | 2223 | 45 | 313 | 106 | 20 | 28.7 | 0.283 |
| G20H012 | 2 | 523 | 51 | 140 | 53 | 244 | 3.7 | 0.405 |
| G30H001 | 2 | 391 | 54 | 70 | 39 | 647 | 4.4 | 0.010 |
| G40H006 | 2 | 538 | 36 | 118 | 53 | 600 | 5.8 | 0.278 |
| G40H014 | 2 | 731 | 43 | 212 | 49 | 252 | 6.6 | 0.464 |

| Catchment Name | Rainfall Seasonality | MAP (mm) | Rainfall Concentration (%) | ACRU Recharge (mm a$^{-1}$) | VEGTER Recharge (mm a$^{-1}$) | Catchment Area (km$^2$) | Average Catchment Slope (°) | Drainage Density (km/km$^2$) |
|---|---|---|---|---|---|---|---|---|
| G50H008 | 2 | 372 | 30 | 27 | 33 | 382 | 2.2 | 0.720 |
| H10H007 | 2 | 1388 | 47 | 226 | 95 | 84 | 19.3 | 0.489 |
| H10H013 | 2 | 977 | 53 | 234 | 78 | 53 | 13.9 | 0.386 |
| H10H017 | 2 | 1745 | 50 | 269 | 103 | 61 | 15.8 | 0.867 |
| H10H018 | 2 | 1608 | 50 | 271 | 101 | 113 | 16.3 | 0.444 |
| H20H001 | 2 | 670 | 53 | 194 | 34 | 697 | 14.2 | 0.466 |
| H20H003 | 2 | 647 | 53 | 205 | 33 | 718 | 14.2 | 0.463 |
| H20H005 | 2 | 1029 | 55 | 252 | 32 | 15 | 22.4 | 0.768 |
| H40H005 | 2 | 649 | 30 | 43 | 45 | 24 | 12.6 | 1.512 |
| H60H008 | 2 | 2313 | 46 | 344 | 100 | 38 | 11.2 | 0.715 |
| H70H001 | 2 | 506 | 33 | 78 | 39 | 9829 | 7.2 | 0.232 |
| H70H003 | 1 | 466 | 15 | 56 | 27 | 450 | 9.1 | 0.328 |
| H90H004 | 1 | 533 | 7 | 53 | 28 | 50 | 13.4 | 0.387 |
| H90H005 | 1 | 579 | 7 | 58 | 40 | 228 | 8.1 | 0.194 |
| J25H005 | 1 | 340 | 8 | 9 | 18 | 253 | 11.0 | 0.311 |
| J35H013 | 1 | 623 | 7 | 19 | 22 | 29 | 13.0 | 0.220 |
| J35H017 | 1 | 429 | 5 | 34 | 29 | 348 | 6.5 | 0.252 |
| J40H003 | 1 | 637 | 7 | 41 | 33 | 95 | 7.7 | 0.151 |
| J40H004 | 1 | 513 | 3 | 45 | 33 | 99 | 7.6 | 0.292 |
| K30H004 | 1 | 942 | 11 | 87 | 68 | 34 | 12.5 | 0.265 |
| K30H005 | 1 | 677 | 5 | 67 | 56 | 78 | 11.1 | 0.060 |
| K40H001 | 1 | 823 | 7 | 97 | 72 | 111 | 6.4 | 0.110 |
| K40H002 | 1 | 1099 | 5 | 124 | 45 | 22 | 13.6 | 1.251 |
| K40H003 | 1 | 711 | 7 | 61 | 52 | 72 | 8.2 | 0.081 |
| K50H002 | 1 | 824 | 5 | 122 | 77 | 133 | 8.5 | 0.220 |
| K60H001 | 1 | 665 | 6 | 86 | 36 | 165 | 10.1 | 0.072 |
| K70H001 | 1 | 1007 | 4 | 170 | 95 | 57 | 11.3 | 0.514 |
| K80H001 | 1 | 1046 | 6 | 202 | 95 | 35 | 12.6 | 0.695 |
| L82H001 | 1 | 872 | 5 | 78 | 83 | 21 | 14.0 | 0.858 |
| L82H002 | 1 | 623 | 6 | 57 | 38 | 52 | 9.7 | 0.200 |
| P40H001 | 1 | 602 | 16 | 16 | 32 | 576 | 3.9 | 0.509 |
| Q92H002 | 6 | 594 | 30 | 31 | 42 | 1245 | 8.7 | 0.104 |
| Q94H019 | 5 | 868 | 33 | 52 | 45 | 76 | 11.4 | 28.699 |
| R10H001 | 5 | 745 | 32 | 67 | 40 | 238 | 7.1 | 0.129 |
| R10H005 | 5 | 838 | 33 | 68 | 54 | 482 | 8.4 | 0.174 |
| R10H006 | 5 | 829 | 32 | 67 | 44 | 100 | 6.6 | 0.178 |
| R10H014 | 5 | 1058 | 33 | 148 | 52 | 70 | 11.4 | 2.069 |
| R20H001 | 5 | 1372 | 34 | 115 | 58 | 29 | 11.0 | 0.189 |
| R20H005 | 5 | 847 | 34 | 62 | 42 | 411 | 4.4 | 0.202 |
| R20H006 | 5 | 826 | 32 | 48 | 36 | 119 | 3.4 | 0.189 |
| R20H008 | 5 | 933 | 36 | 118 | 58 | 61 | 5.8 | 0.030 |
| S30H006 | 5 | 508 | 45 | 6 | 31 | 2170 | 4.9 | 0.097 |
| S60H003 | 5 | 676 | 42 | 29 | 38 | 215 | 4.5 | 0.172 |
| T10H004 | 5 | 776 | 47 | 37 | 51 | 4908 | 5.5 | 0.131 |

| Catchment Name | Rainfall Seasonality | MAP (mm) | Rainfall Concentration (%) | ACRU Recharge (mm a$^{-1}$) | VEGTER Recharge (mm a$^{-1}$) | Catchment Area (km$^2$) | Average Catchment Slope (°) | Drainage Density (km/km$^2$) |
|---|---|---|---|---|---|---|---|---|
| T20H002 | 4 | 847 | 47 | 59 | 53 | 1199 | 5.5 | 0.114 |
| T30H004 | 4 | 796 | 53 | 47 | 52 | 1029 | 6.4 | 0.426 |
| T30H008 | 4 | 777 | 56 | 21 | 47 | 2471 | 5.1 | 0.368 |
| T30H009 | 5 | 903 | 49 | 38 | 65 | 307 | 9.0 | 0.176 |
| T40H001 | 4 | 933 | 49 | 122 | 81 | 715 | 5.6 | 0.451 |
| T50H002 | 4 | 907 | 50 | 107 | 65 | 867 | 6.8 | 0.455 |
| T50H003 | 4 | 1034 | 57 | 121 | 95 | 140 | 5.9 | 0.481 |
| T50H004 | 4 | 1021 | 57 | 123 | 92 | 545 | 7.2 | 0.160 |
| U10H006 | 4 | 958 | 52 | 87 | 81 | 4349 | 8.6 | 0.515 |
| U20H001 | 4 | 976 | 52 | 85 | 94 | 937 | 5.0 | 0.483 |
| U20H006 | 4 | 1042 | 52 | 120 | 93 | 339 | 4.9 | 0.476 |
| U20H007 | 4 | 989 | 53 | 86 | 95 | 358 | 4.2 | 0.461 |
| U20H011 | 4 | 921 | 50 | 61 | 94 | 176 | 7.0 | 1.573 |
| U20H012 | 4 | 978 | 49 | 77 | 67 | 438 | 3.7 | 0.454 |
| U20H013 | 4 | 1005 | 53 | 105 | 95 | 299 | 6.0 | 0.422 |
| U30H002 | 4 | 975 | 45 | 96 | 65 | 356 | 7.4 | 0.500 |
| U40H002 | 4 | 926 | 51 | 99 | 84 | 316 | 4.3 | 0.471 |
| U70H007 | 4 | 1048 | 49 | 116 | 84 | 114 | 7.3 | 0.362 |
| V10H001 | 4 | 967 | 58 | 82 | 72 | 4176 | 7.1 | 0.421 |
| V10H002 | 4 | 1136 | 57 | 125 | 95 | 1689 | 10.2 | 0.446 |
| V10H009 | 4 | 791 | 57 | 16 | 50 | 196 | 3.9 | 0.383 |
| V10H031 | 4 | 820 | 58 | 14 | 65 | 162 | 2.7 | 0.371 |
| V10H038 | 4 | 850 | 59 | 41 | 59 | 1644 | 4.0 | 0.368 |
| V20H001 | 4 | 851 | 55 | 62 | 73 | 1976 | 4.7 | 0.442 |
| V20H005 | 4 | 1027 | 56 | 127 | 95 | 260 | 6.0 | 0.481 |
| V30H002 | 3 | 866 | 58 | 73 | 64 | 1518 | 4.9 | 1.109 |
| V30H003 | 4 | 856 | 59 | 58 | 65 | 850 | 4.0 | 0.375 |
| V30H005 | 3 | 909 | 58 | 106 | 65 | 676 | 4.4 | 0.368 |
| V30H007 | 4 | 966 | 59 | 104 | 65 | 129 | 6.2 | 0.359 |
| V30H009 | 4 | 922 | 59 | 69 | 65 | 148 | 2.7 | 0.348 |
| V60H003 | 4 | 850 | 59 | 43 | 52 | 312 | 4.5 | 0.138 |
| V60H004 | 4 | 864 | 60 | 45 | 59 | 658 | 4.6 | 0.387 |
| V60H006 | 4 | 892 | 60 | 65 | 65 | 109 | 5.3 | 0.960 |
| V70H012 | 4 | 815 | 56 | 21 | 61 | 196 | 4.5 | 0.488 |
| V70H016 | 4 | 1101 | 57 | 153 | 95 | 121 | 8.7 | 0.552 |
| V70H017 | 4 | 1177 | 57 | 191 | 95 | 276 | 10.2 | 0.584 |
| W41H004 | 3 | 937 | 56 | 108 | 86 | 948 | 3.5 | 0.392 |
| W51H006 | 3 | 905 | 55 | 85 | 66 | 180 | 3.4 | 0.399 |
| W53H004 | 3 | 815 | 58 | 49 | 56 | 460 | 2.6 | 0.320 |
| W54H008 | 3 | 867 | 58 | 91 | 66 | 118 | 2.0 | 0.320 |
| X20H005 | 3 | 1081 | 57 | 192 | 120 | 642 | 6.2 | 0.300 |
| X20H008 | 3 | 1020 | 57 | 132 | 95 | 180 | 7.4 | 0.358 |
| X20H010 | 3 | 1109 | 57 | 210 | 96 | 126 | 5.4 | 0.391 |
| X20H011 | 3 | 757 | 60 | 48 | 88 | 402 | 3.3 | 0.244 |

| Catchment Name | Rainfall Seasonality | MAP (mm) | Rainfall Concentration (%) | ACRU Recharge (mm.a$^{-1}$) | VEGTER Recharge (mm.a$^{-1}$) | Catchment Area (km$^2$) | Average Catchment Slope (°) | Drainage Density (km/km$^2$) |
|---|---|---|---|---|---|---|---|---|
| X20H012 | 3 | 755 | 60 | 48 | 95 | 91 | 3.0 | 0.399 |
| X20H013 | 3 | 766 | 59 | 56 | 97 | 1518 | 7.3 | 0.335 |
| X20H014 | 3 | 991 | 58 | 138 | 134 | 250 | 10.1 | 0.278 |
| X20H015 | 3 | 884 | 59 | 103 | 109 | 1554 | 7.3 | 0.276 |
| X20H022 | 3 | 909 | 58 | 81 | 75 | 1639 | 6.8 | 0.340 |
| X20H024 | 3 | 1151 | 57 | 180 | 112 | 80 | 7.8 | 4.328 |
| X20H027 | 3 | 1069 | 57 | 147 | 132 | 78 | 10.8 | 0.223 |
| X20H031 | 3 | 927 | 57 | 87 | 95 | 262 | 5.2 | 0.333 |
| X30H001 | 4 | 1213 | 56 | 273 | 162 | 174 | 10.4 | 0.371 |
| X30H003 | 4 | 1406 | 56 | 285 | 180 | 52 | 4.6 | 0.296 |
| X30H006 | 4 | 1189 | 56 | 239 | 148 | 766 | 7.1 | 0.343 |
| X30H007 | 4 | 1250 | 56 | 204 | 112 | 46 | 4.5 | 0.363 |

**Units for the catchment characteristics:**

| | | |
|---|---|---|
| Rainfall Seasonality | 1 | All Year |
| | 2 | Winter |
| | 3 | Early Summer |
| | 4 | Mid Summer |
| | 5 | Late Summer |
| | 6 | Very Late Summer |
| MAP | mm | |
| Rainfall Concentration | % | |
| Recharge | mm.a$^{-1}$ | |
| Area | km$^2$ | |
| Slope | degrees (°) | |
| Drainage Density | km/km$^2$ | |

**Appendix 2.10** : Summary of the catchments which produce MRCs for the wet and dry seasons. 0 = Does not produce; 1 = Does produce

| Catchment | Wet Season | Dry Season | Wet Season Only | Dry Season Only |
|---|---|---|---|---|
| A2H029 | 0 | 0 | 0 | 0 |
| A2H032 | 0 | 0 | 0 | 0 |
| A2H039 | 0 | 0 | 0 | 0 |
| A2H049 | 0 | 0 | 0 | 0 |
| A2H050 | 0 | 0 | 0 | 0 |
| A3H001 | 1 | 0 | 1 | 0 |
| A4H002 | 1 | 1 | 0 | 0 |
| A4H005 | 1 | 1 | 0 | 0 |
| A4H008 | 1 | 1 | 0 | 0 |
| A5H004 | 1 | 1 | 0 | 0 |
| A6H011 | 1 | 1 | 0 | 0 |
| A6H012 | 1 | 1 | 0 | 0 |
| A6H018 | 0 | 0 | 0 | 0 |
| A6H019 | 0 | 0 | 0 | 0 |
| A6H020 | 0 | 0 | 0 | 0 |
| A9H002 | 1 | 1 | 0 | 0 |
| A9H003 | 1 | 1 | 0 | 0 |
| A9H004 | 1 | 1 | 0 | 0 |
| B1H001 | 1 | 1 | 0 | 0 |
| B1H002 | 0 | 1 | 0 | 1 |
| B1H004 | 1 | 1 | 0 | 0 |
| B2H001 | 1 | 1 | 0 | 0 |
| B4H005 | 1 | 0 | 1 | 0 |
| B5H002 | 1 | 1 | 0 | 0 |
| B6H001 | 1 | 1 | 0 | 0 |
| B6H002 | 1 | 1 | 0 | 0 |
| B6H003 | 1 | 1 | 0 | 0 |
| B6H006 | 0 | 0 | 0 | 0 |
| B7H004 | 1 | 1 | 0 | 0 |
| B7H008 | 1 | 1 | 0 | 0 |
| B7H010 | 1 | 0 | 1 | 0 |
| B9H001 | 0 | 0 | 0 | 0 |
| C1H007 | 1 | 1 | 0 | 0 |
| C2H026 | 0 | 0 | 0 | 0 |
| C2H027 | 0 | 0 | 0 | 0 |
| C2H028 | 0 | 0 | 0 | 0 |
| C2H067 | 0 | 0 | 0 | 0 |
| C3H003 | 1 | 1 | 0 | 0 |
| C5H007 | 0 | 0 | 0 | 0 |
| C5H008 | 0 | 0 | 0 | 0 |
| C5H012 | 1 | 1 | 0 | 0 |
| C6H003 | 1 | 1 | 0 | 0 |

| Catchment | Wet Season | Dry Season | Wet Season Only | Dry Season Only |
|---|---|---|---|---|
| C7H003 | 0 | 0 | 0 | 0 |
| C8H003 | 1 | 1 | 0 | 0 |
| C8H012 | 1 | 0 | 1 | 0 |
| E1H006 | 0 | 1 | 0 | 1 |
| E2H002 | 1 | 1 | 0 | 0 |
| G1H003 | 0 | 1 | 0 | 1 |
| G1H007 | 1 | 1 | 0 | 0 |
| G1H008 | 0 | 0 | 0 | 0 |
| G1H009 | 0 | 0 | 0 | 0 |
| G1H010 | 0 | 0 | 0 | 0 |
| G1H011 | 0 | 1 | 0 | 1 |
| G1H012 | 0 | 0 | 0 | 0 |
| G1H014 | 0 | 0 | 0 | 0 |
| G1H015 | 0 | 0 | 0 | 0 |
| G1H016 | 0 | 0 | 0 | 0 |
| G1H017 | 0 | 0 | 0 | 0 |
| G1H018 | 0 | 0 | 0 | 0 |
| G2H008 | 1 | 1 | 0 | 0 |
| G2H012 | 0 | 1 | 0 | 1 |
| G3H001 | 0 | 1 | 0 | 1 |
| G4H006 | 1 | 1 | 0 | 0 |
| G4H008 | 0 | 0 | 0 | 0 |
| G4H009 | 0 | 0 | 0 | 0 |
| G4H010 | 0 | 0 | 0 | 0 |
| G4H012 | 0 | 0 | 0 | 0 |
| G4H013 | 0 | 0 | 0 | 0 |
| G4H014 | 0 | 1 | 0 | 1 |
| G5H008 | 0 | 1 | 0 | 1 |
| H1H007 | 1 | 1 | 0 | 0 |
| H1H013 | 0 | 1 | 0 | 1 |
| H1H017 | 1 | 0 | 1 | 0 |
| H1H018 | 1 | 1 | 0 | 0 |
| H2H001 | 1 | 1 | 0 | 0 |
| H2H005 | 0 | 1 | 0 | 1 |
| H3H001 | 0 | 0 | 0 | 0 |
| H3H004 | 0 | 0 | 0 | 0 |
| H3H005 | 0 | 0 | 0 | 0 |
| H4H005 | 0 | 1 | 0 | 1 |
| H4H012 | 0 | 0 | 0 | 0 |
| H6H008 | 1 | 1 | 0 | 0 |
| H6H010 | 0 | 0 | 0 | 0 |
| H7H001 | 1 | 1 | 0 | 0 |
| H7H003 | 1 | 1 | 0 | 0 |
| H7H004 | 1 | 0 | 1 | 0 |
| H9H004 | 1 | 1 | 0 | 0 |
| H9H005 | 1 | 1 | 0 | 0 |

| Catchment | Wet Season | Dry Season | Wet Season Only | Dry Season Only |
|---|---|---|---|---|
| J1H015 | 0 | 0 | 0 | 0 |
| J2H005 | 1 | 1 | 0 | 0 |
| J2H006 | 0 | 0 | 0 | 0 |
| J2H007 | 0 | 0 | 0 | 0 |
| J3H013 | 1 | 1 | 0 | 0 |
| J3H017 | 1 | 0 | 1 | 0 |
| J4H003 | 1 | 1 | 0 | 0 |
| J4H004 | 1 | 0 | 1 | 0 |
| K3H002 | 0 | 0 | 0 | 0 |
| K3H004 | 1 | 1 | 0 | 0 |
| K3H005 | 1 | 1 | 0 | 0 |
| K4H001 | 1 | 1 | 0 | 0 |
| K4H002 | 1 | 1 | 0 | 0 |
| K4H003 | 1 | 1 | 0 | 0 |
| K5H002 | 1 | 1 | 0 | 0 |
| K6H001 | 1 | 1 | 0 | 0 |
| K7H001 | 1 | 1 | 0 | 0 |
| K8H001 | 1 | 1 | 0 | 0 |
| K8H002 | 0 | 0 | 0 | 0 |
| L1H001 | 0 | 0 | 0 | 0 |
| L6H001 | 0 | 0 | 0 | 0 |
| L8H001 | 1 | 1 | 0 | 0 |
| L8H002 | 1 | 1 | 0 | 0 |
| P4H001 | 1 | 1 | 0 | 0 |
| Q1H001 | 0 | 0 | 0 | 0 |
| Q3H004 | 0 | 0 | 0 | 0 |
| Q9H019 | 1 | 1 | 0 | 0 |
| R1H001 | 1 | 1 | 0 | 0 |
| R1H005 | 1 | 1 | 0 | 0 |
| R1H006 | 1 | 0 | 1 | 0 |
| R1H007 | 0 | 0 | 0 | 0 |
| R1H014 | 1 | 1 | 0 | 0 |
| R2H001 | 1 | 1 | 0 | 0 |
| R2H005 | 1 | 1 | 0 | 0 |
| R2H006 | 1 | 1 | 0 | 0 |
| R2H008 | 1 | 1 | 0 | 0 |
| R2H012 | 0 | 0 | 0 | 0 |
| S3H006 | 1 | 0 | 1 | 0 |
| S6H003 | 1 | 1 | 0 | 0 |
| T1H004 | 1 | 1 | 0 | 0 |
| T2H002 | 1 | 1 | 0 | 0 |
| T3H004 | 1 | 1 | 0 | 0 |
| T3H008 | 1 | 1 | 0 | 0 |
| T3H009 | 1 | 1 | 0 | 0 |
| T4H001 | 1 | 1 | 0 | 0 |
| T5H002 | 1 | 1 | 0 | 0 |

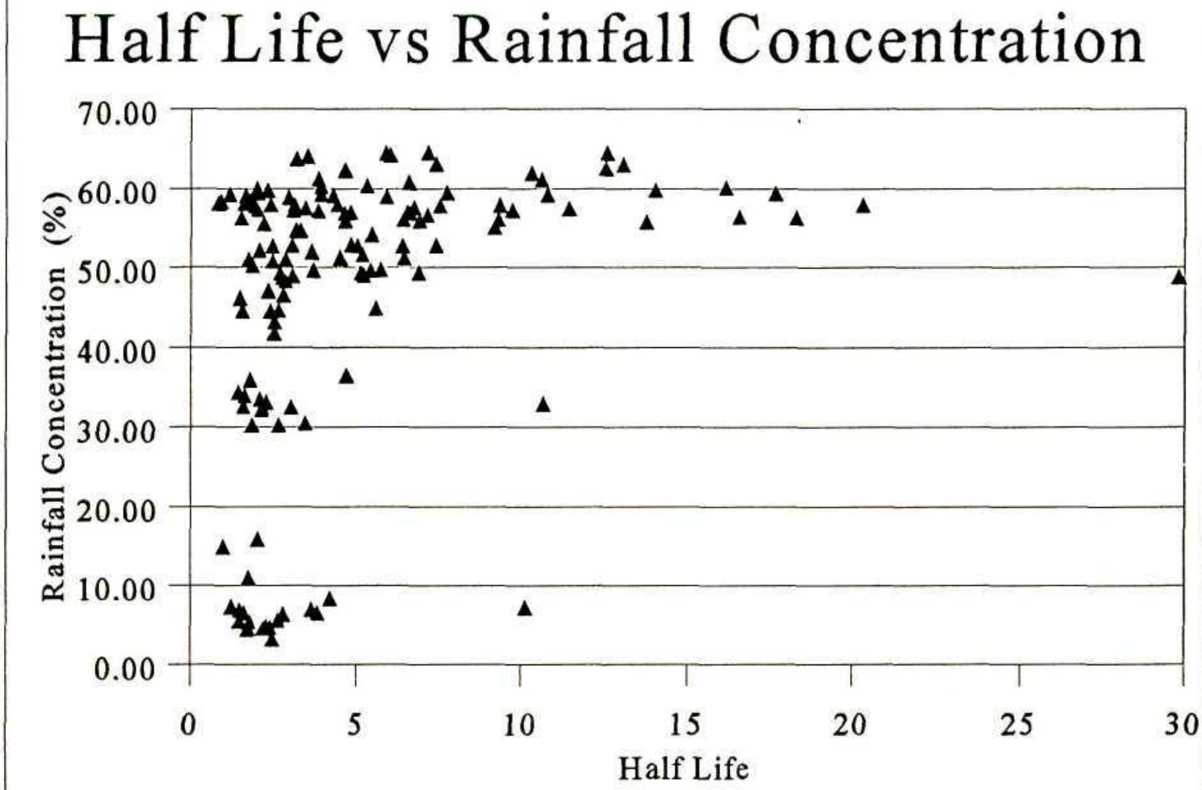
| Catchment | Wet Season | Dry Season | Wet Season Only | Dry Season Only |
|---|---|---|---|---|
| T5H003 | 1 | 1 | 0 | 0 |
| T5H004 | 1 | 1 | 0 | 0 |
| U1H006 | 1 | 1 | 0 | 0 |
| U2H001 | 1 | 1 | 0 | 0 |
| U2H006 | 1 | 1 | 0 | 0 |
| U2H007 | 1 | 1 | 0 | 0 |
| U2H011 | 1 | 1 | 0 | 0 |
| U2H012 | 1 | 1 | 0 | 0 |
| U2H013 | 1 | 1 | 0 | 0 |
| U3H002 | 1 | 1 | 0 | 0 |
| U4H002 | 1 | 1 | 0 | 0 |
| U7H007 | 1 | 1 | 0 | 0 |
| V1H001 | 1 | 1 | 0 | 0 |
| V1H002 | 1 | 0 | 1 | 0 |
| V1H009 | 1 | 1 | 0 | 0 |
| V1H010 | 0 | 0 | 0 | 0 |
| V1H031 | 0 | 1 | 0 | 1 |
| V1H038 | 1 | 1 | 0 | 0 |
| V2H001 | 1 | 1 | 0 | 0 |
| V3H002 | 1 | 1 | 0 | 0 |
| V3H003 | 1 | 1 | 0 | 0 |
| V3H005 | 1 | 1 | 0 | 0 |
| V3H007 | 1 | 1 | 0 | 0 |
| V3H009 | 1 | 1 | 0 | 0 |
| V6H003 | 1 | 1 | 0 | 0 |
| V6H004 | 1 | 1 | 0 | 0 |
| V6H006 | 1 | 1 | 0 | 0 |
| V7H012 | 1 | 1 | 0 | 0 |
| V7H016 | 1 | 0 | 1 | 0 |
| V7H017 | 1 | 1 | 0 | 0 |
| W1H004 | 0 | 0 | 0 | 0 |
| W3H014 | 0 | 0 | 0 | 0 |
| W4H004 | 1 | 1 | 0 | 0 |
| W5H001 | 0 | 0 | 0 | 0 |
| W5H004 | 1 | 1 | 0 | 0 |
| W5H006 | 1 | 1 | 0 | 0 |
| W5H008 | 1 | 1 | 0 | 0 |
| X1H003 | 0 | 0 | 0 | 0 |
| X2H005 | 1 | 1 | 0 | 0 |
| X2H008 | 1 | 1 | 0 | 0 |
| X2H010 | 1 | 1 | 0 | 0 |
| X2H011 | 1 | 1 | 0 | 0 |
| X2H012 | 1 | 1 | 0 | 0 |
| X2H013 | 1 | 1 | 0 | 0 |
| X2H014 | 1 | 1 | 0 | 0 |
| X2H015 | 1 | 1 | 0 | 0 |

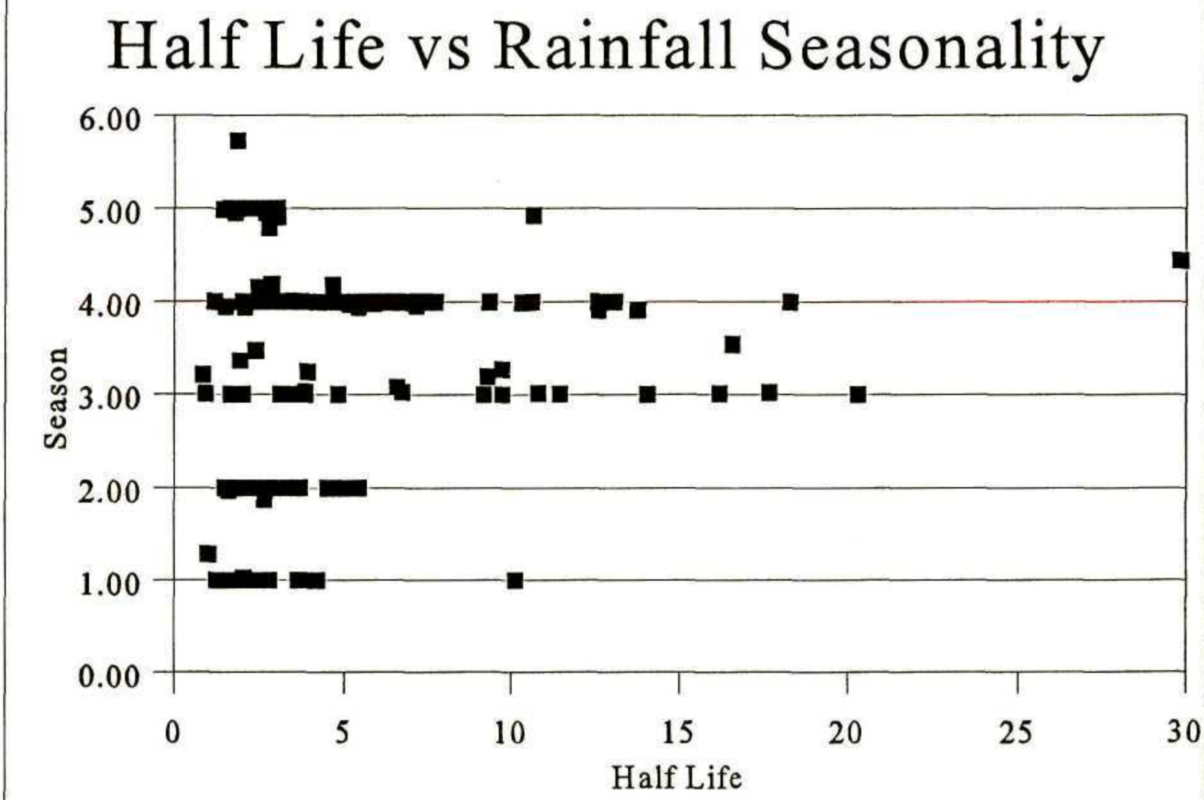
| Catchment | Wet Season | Dry Season | Wet Season Only | Dry Season Only |
|---|---|---|---|---|
| X2H022 | 1 | 1 | 0 | 0 |
| X2H024 | 0 | 1 | 0 | 1 |
| X2H025 | 1 | 1 | 0 | 0 |
| X2H026 | 1 | 1 | 0 | 0 |
| X2H027 | 1 | 1 | 0 | 0 |
| X2H028 | 0 | 0 | 0 | 0 |
| X2H031 | 1 | 1 | 0 | 0 |
| X3H001 | 1 | 1 | 0 | 0 |
| X3H002 | 0 | 0 | 0 | 0 |
| X3H003 | 1 | 1 | 0 | 0 |
| X3H006 | 1 | 1 | 0 | 0 |
| X3H007 | 0 | 1 | 0 | 1 |

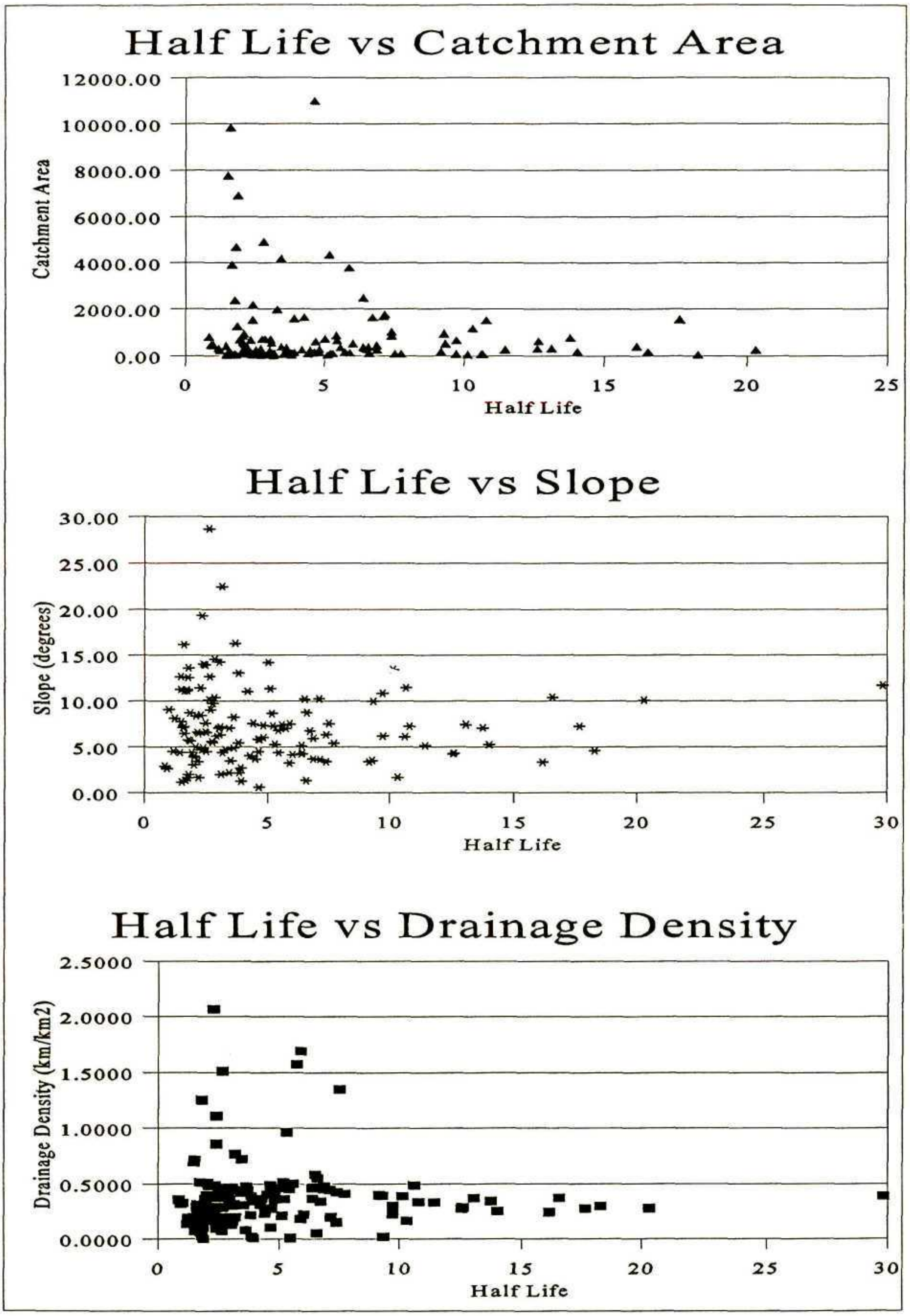
**Appendix 3.1** : List of catchments where the expected MRC trends are reversed, *ie.* the Dry season MRC is steeper than the Wet season MRC

| Catchment Numbers | |
|---|---|
| Winter Rainfall Regions | Other Rainfall Regions |
| G1H007 | H9H004 |
| G2H008 | Q9H001 |
| G4H006 | R2H008 |
| H1H007 | T5H002 |
| H1H018 | U2H006 |
| H2H001 | V1H038 |
| H2H003 | V6H003 |
| H6H008 | |

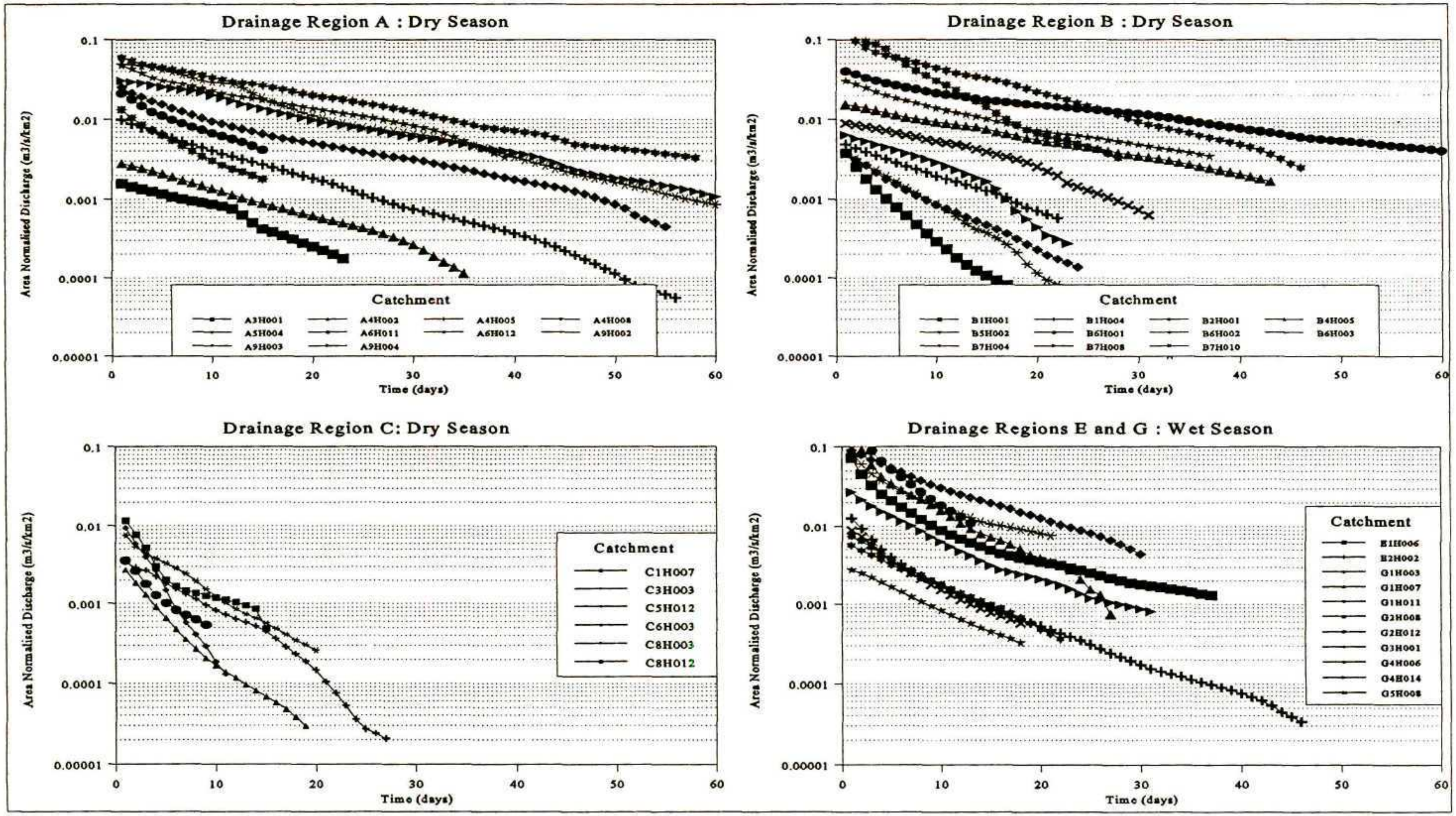
**Appendix 3.2**: Plots of the climatic and morphological variables versus the half life

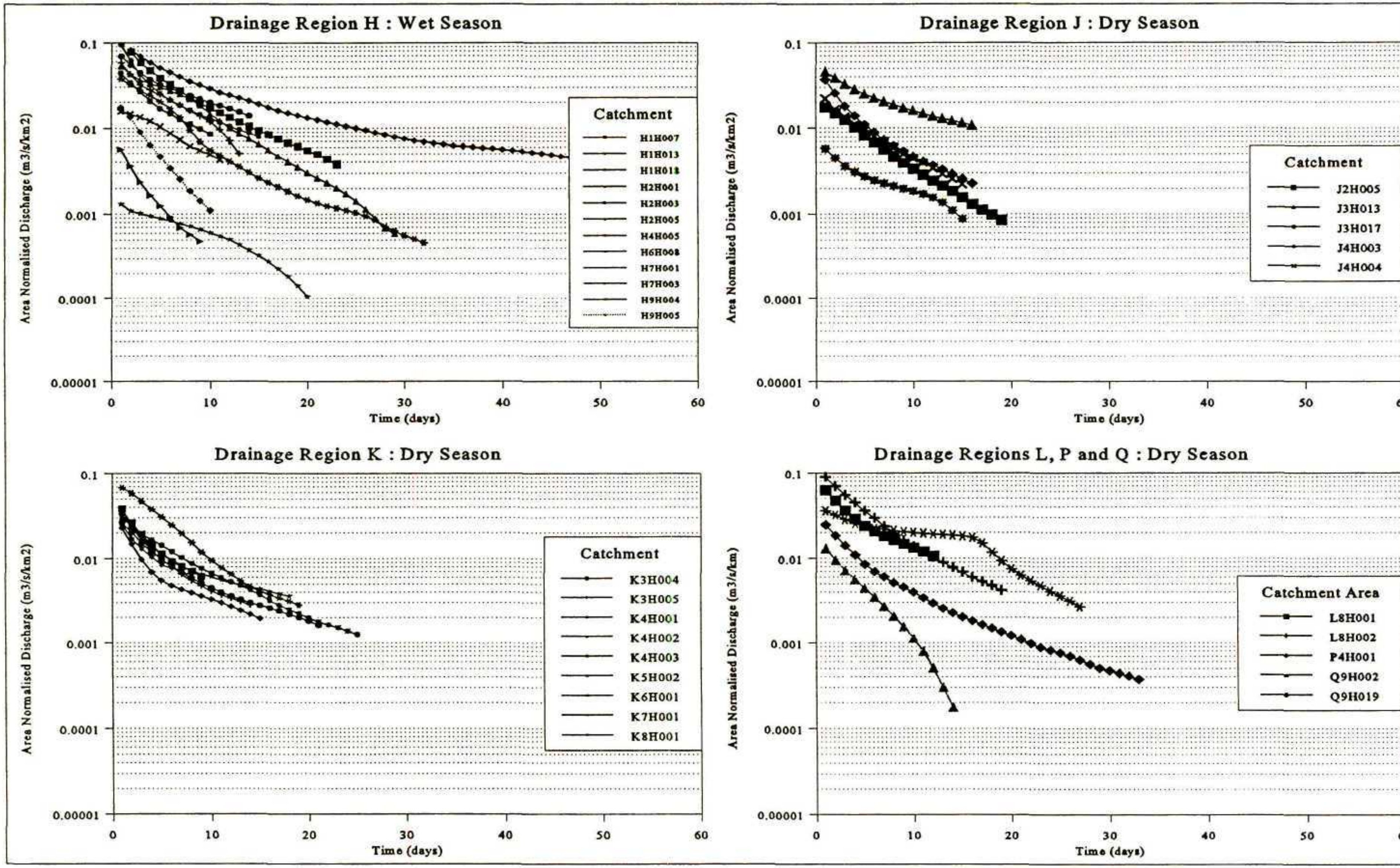


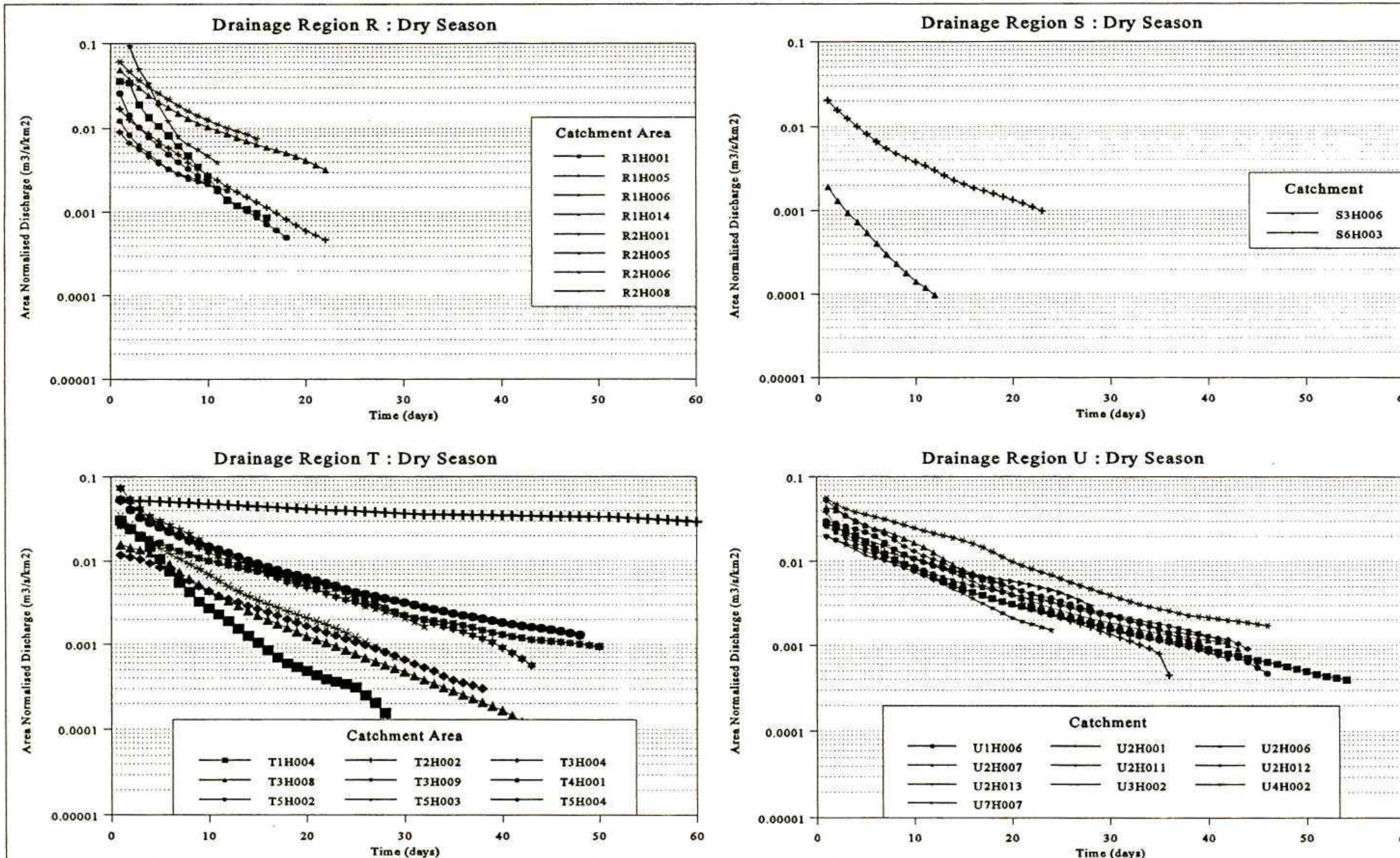

Half Life vs Catchment Area
Catchment Area
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0
5
10
15
20
25
Half Life
Half Life vs Slope
Slope (degrees)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5
10
15
20
25
30
Half Life
Half Life vs Drainage Density
Drainage Density (km/km2)
2.5000
2.0000
1.5000
1.0000
0.5000
0.0000
0
5
10
15
20
25
30
Half Life

**Appendix 3.3** : MRCs per drainage region

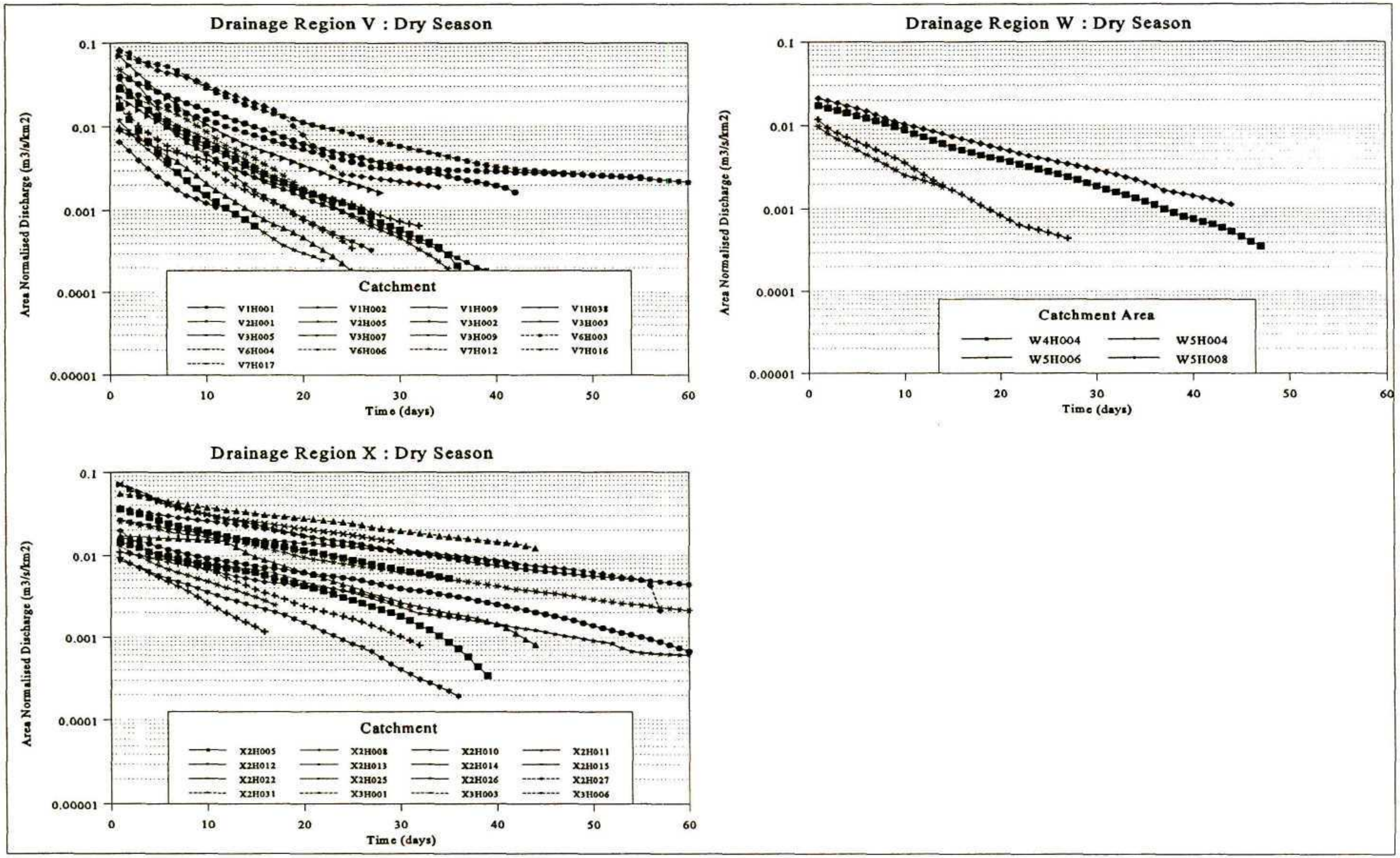




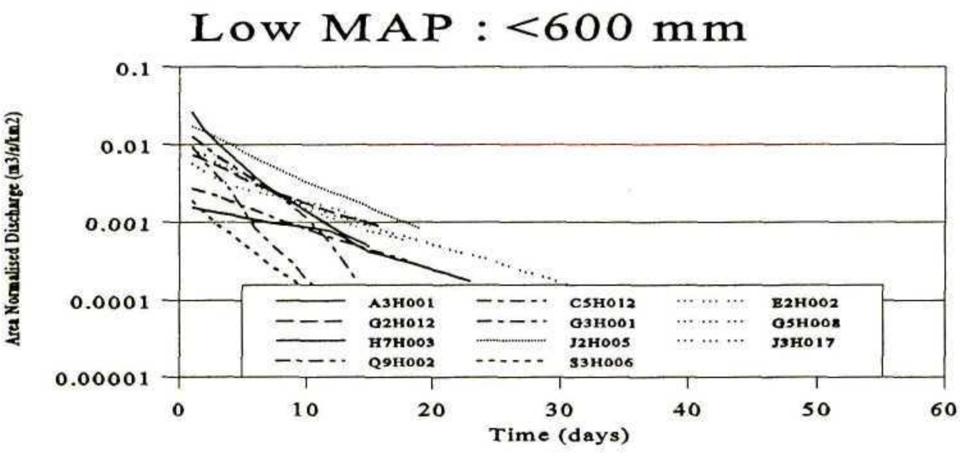
Drainage Region H : Wet Season
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Catchment
H1H007
H1H013
H1H018
H2H001
H2H003
H2H005
H4H005
H6H008
H7H001
H7H003
H9H004
H9H005
Drainage Region J : Dry Season
Area Normalised Discharge (m3/s/km2)
Time (days)
Catchment
J2H005
J3H013
J3H017
J4H003
J4H004
Drainage Region K : Dry Season
Area Normalised Discharge (m3/s/km2)
Time (days)
Catchment
K3H004
K3H005
K4H001
K4H002
K4H003
K5H002
K6H001
K7H001
K8H001
Drainage Regions L, P and Q : Dry Season
Area Normalised Discharge (m3/s/km)
Time (days)
Catchment Area
L8H001
L8H002
P4H001
Q9H002
Q9H019

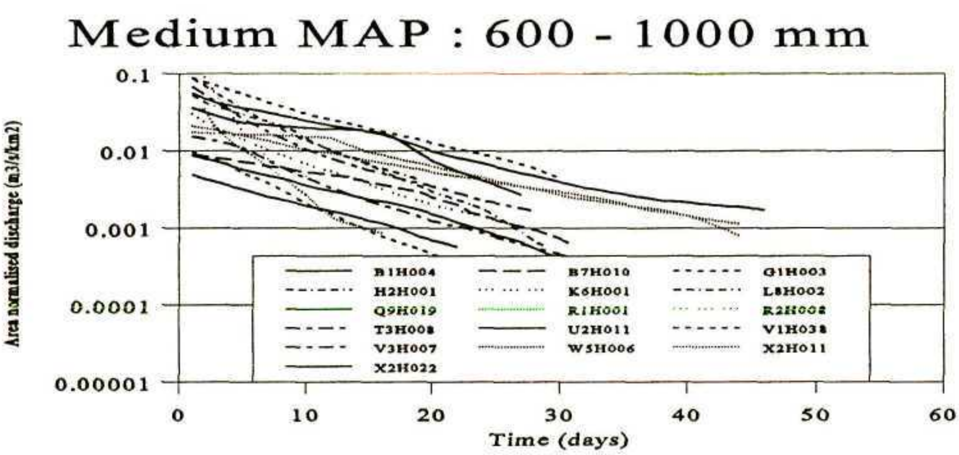


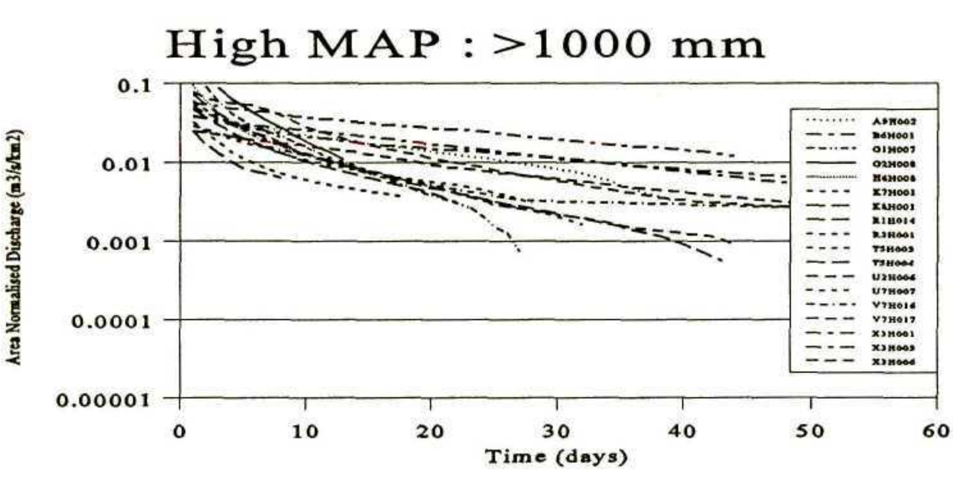
Drainage Region R : Dry Season
Catchment Area
R1H001
R1H005
R1H006
R1H014
R2H001
R2H005
R2H006
R2H008
Drainage Region S : Dry Season
Catchment
S3H006
S6H003
Drainage Region T : Dry Season
Catchment Area
T1H004
T2H002
T3H004
T3H008
T3H009
T4H001
T5H002
T5H003
T5H004
Drainage Region U : Dry Season
Catchment
U1H006
U2H001
U2H006
U2H007
U2H011
U2H012
U2H013
U3H002
U4H002
U7H007
Area Normalised Discharge (m3/s/km2)
Time (days)

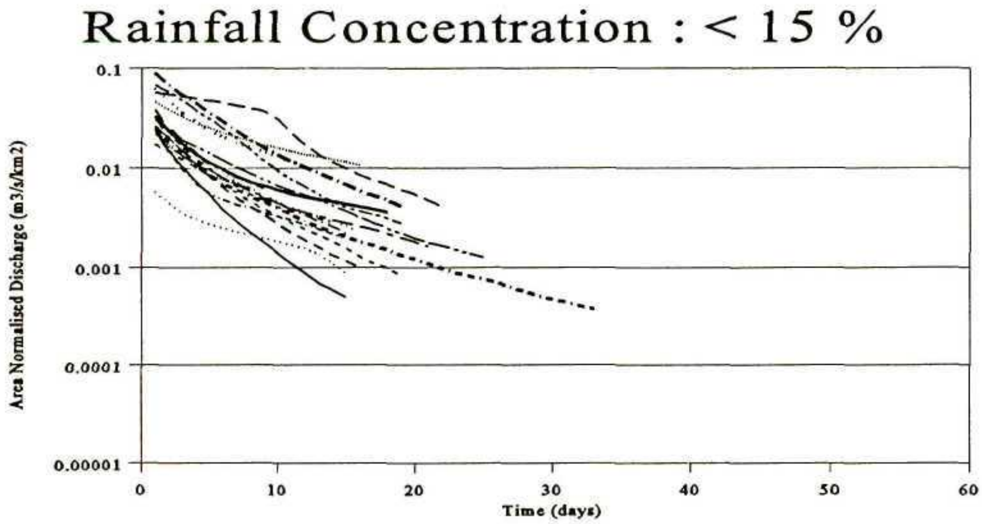

Drainage Region V : Dry Season
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Catchment
V1H001
V1H002
V1H009
V1H038
V2H001
V2H005
V3H002
V3H003
V3H005
V3H007
V3H009
V6H003
V6H004
V6H006
V7H012
V7H016
V7H017
Drainage Region W : Dry Season
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Catchment Area
W4H004
W5H004
W5H006
W5H008
Drainage Region X : Dry Season
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Catchment
X2H005
X2H008
X2H010
X2H011
X2H012
X2H013
X2H014
X2H015
X2H022
X2H025
X2H026
X2H027
X2H031
X3H001
X3H003
X3H006

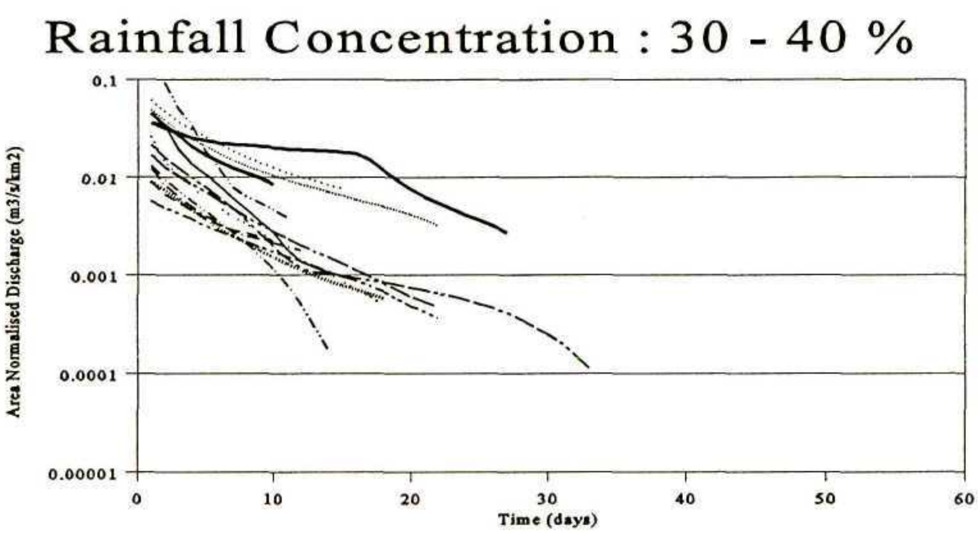
**Appendix 3.4** : Graphs of the MRCs grouped according to climatic parameters

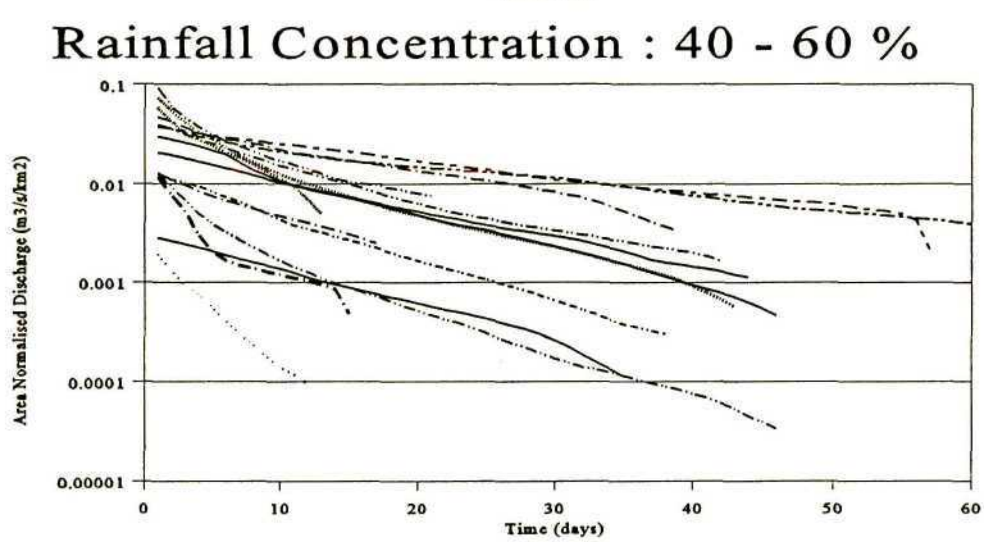


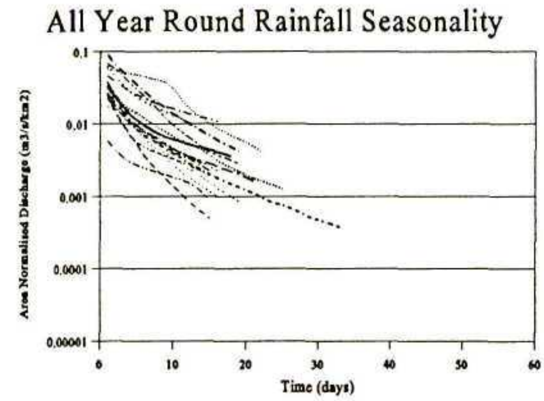



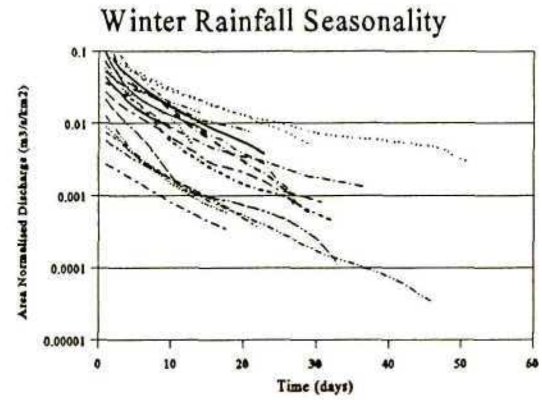

Rainfall Concentration : < 15 %
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)


Rainfall Concentration : 30 - 40 %
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)

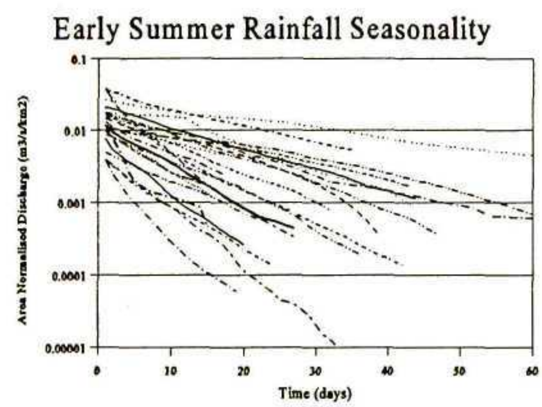

Rainfall Concentration : 40 - 60 %
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)


All Year Round Rainfall Seasonality
0.1
0.01
0.001
0.0001
0.00001
Area Normalised Discharge (m3/s/km2)
0
10
20
30
40
50
60
Time (days)

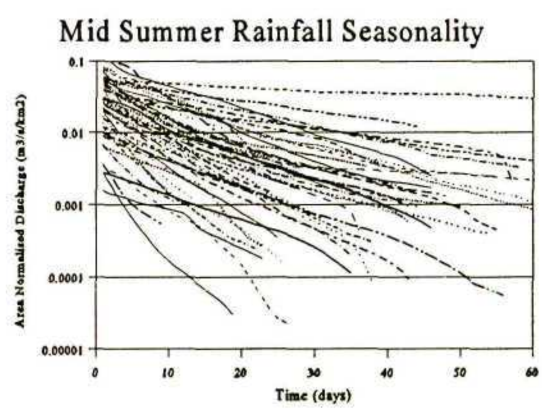
(A)


Winter Rainfall Seasonality
0.1
0.01
0.001
0.0001
0.00001
Area Normalised Discharge (m3/s/km2)
0
10
20
30
40
50
60
Time (days)

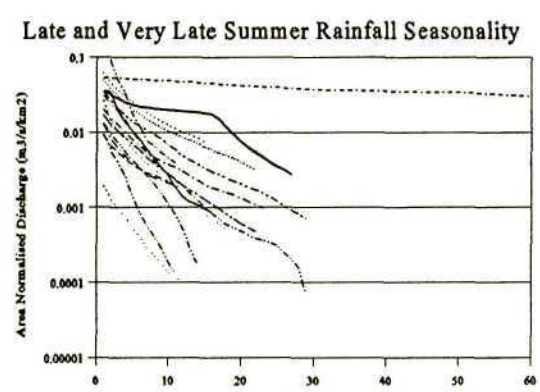
(B)


Early Summer Rainfall Seasonality
0.1
0.01
0.001
0.0001
0.00001
Area Normalised Discharge (m3/s/km2)
0
10
20
30
40
50
60
Time (days)

(C)

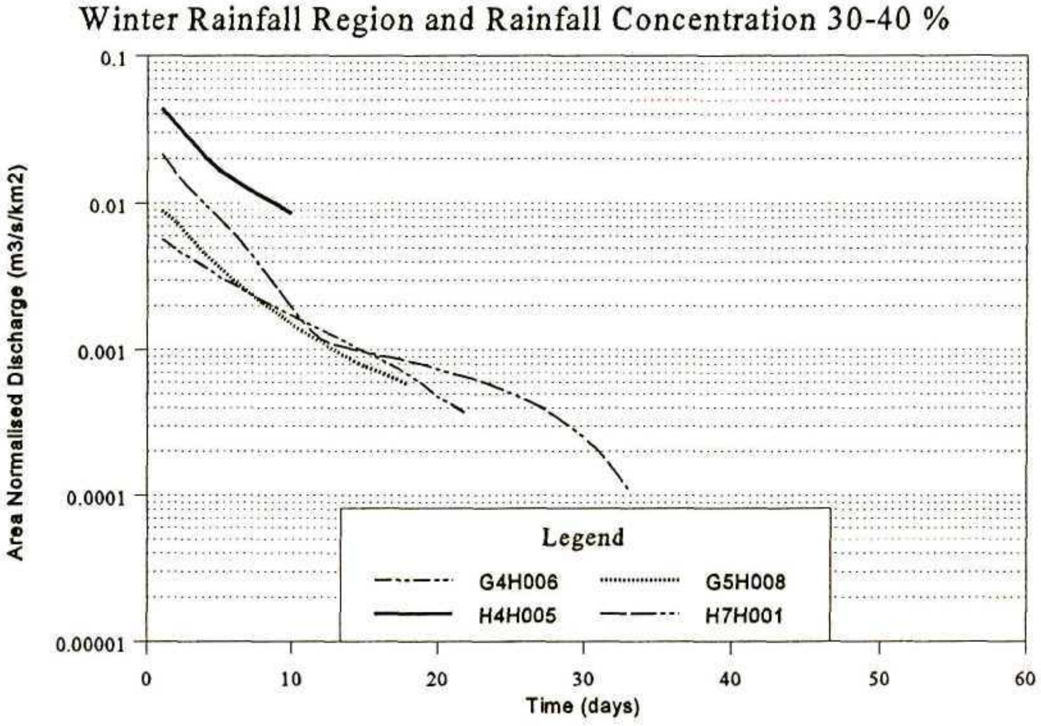

Mid Summer Rainfall Seasonality
0.1
0.01
0.001
0.0001
0.00001
Area Normalised Discharge (m3/s/km2)
0
10
20
30
40
50
60
Time (days)

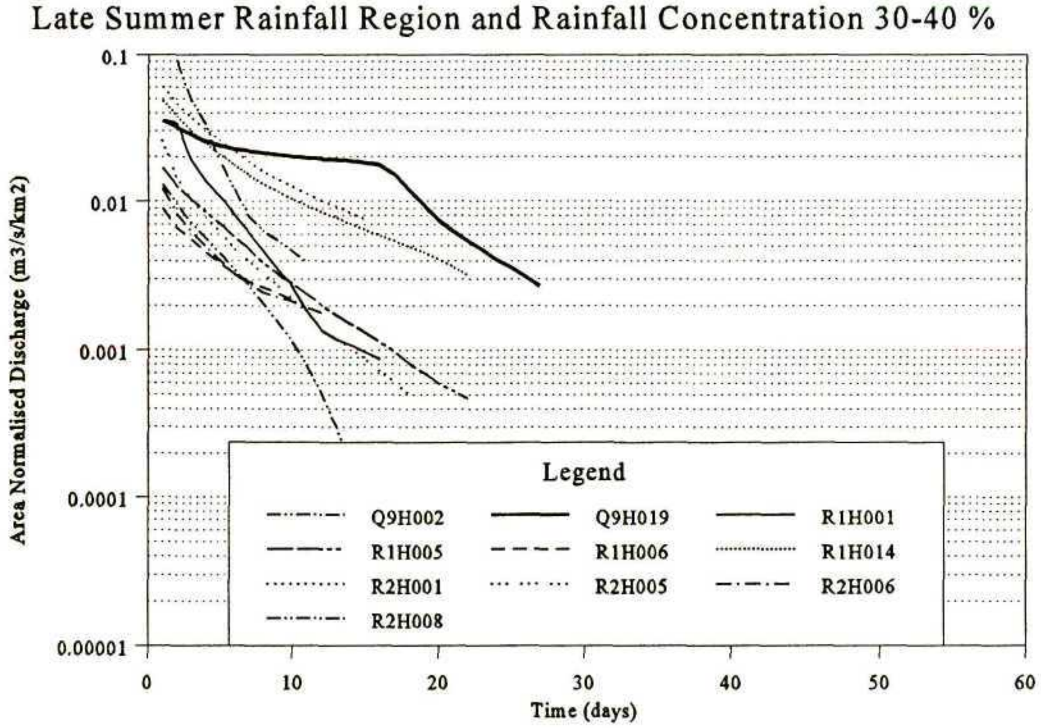
(D)


Late and Very Late Summer Rainfall Seasonality
0.1
0.01
0.001
0.0001
0.00001
Area Normalised Discharge (m3/s/km2)
0
10
20
30
40
50
60
Time (days)

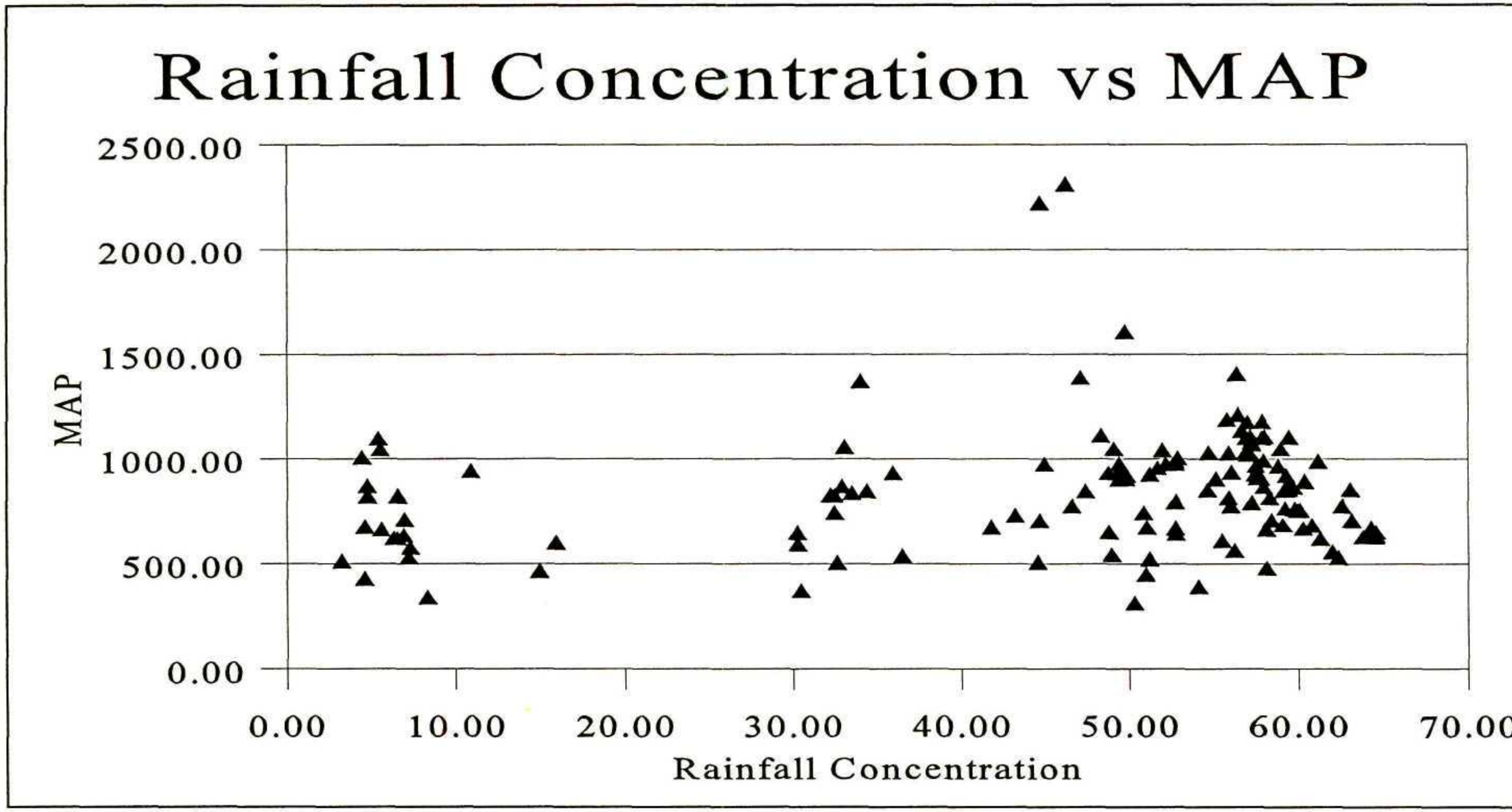
(E)

**Appendix 3.5** : Graphs of the MRCs for groups 2 and 3 identified using the rainfall concentration versus rainfall seasonality plot

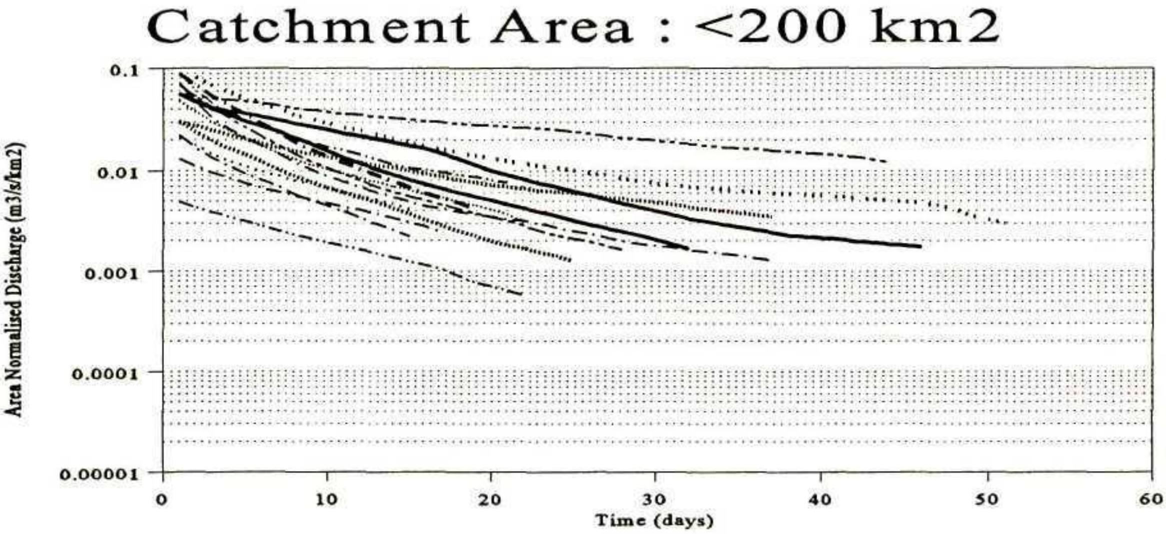


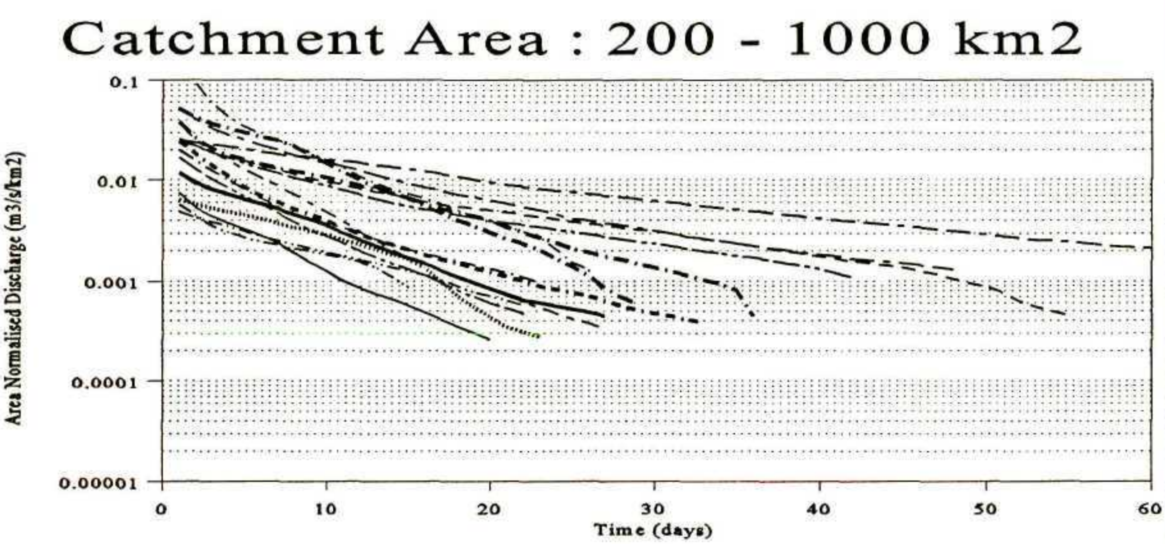



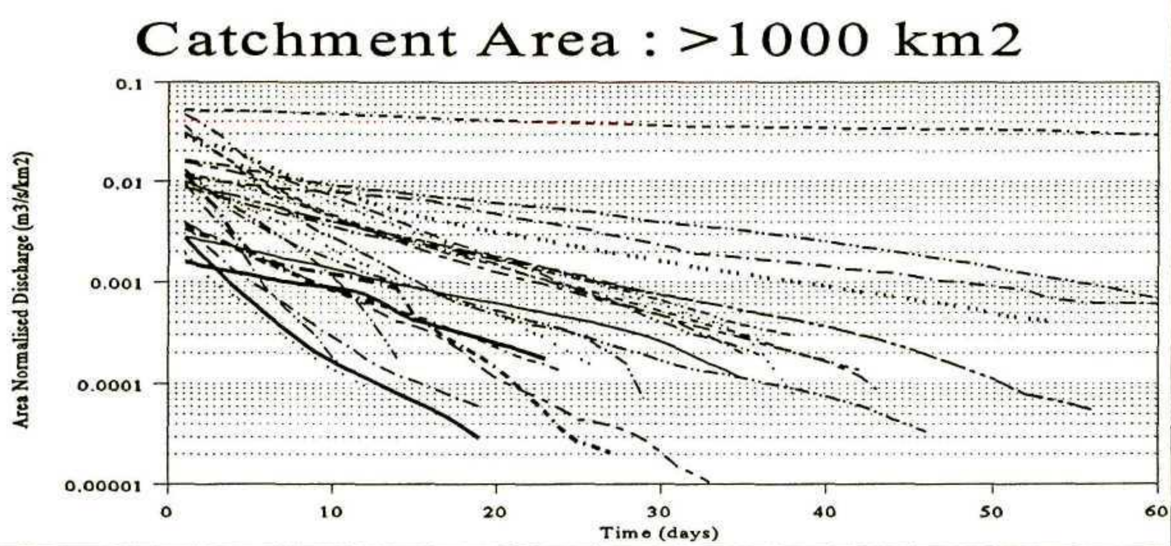
**Appendix 3.6** :	Plot of the rainfall concentration versus the MAP

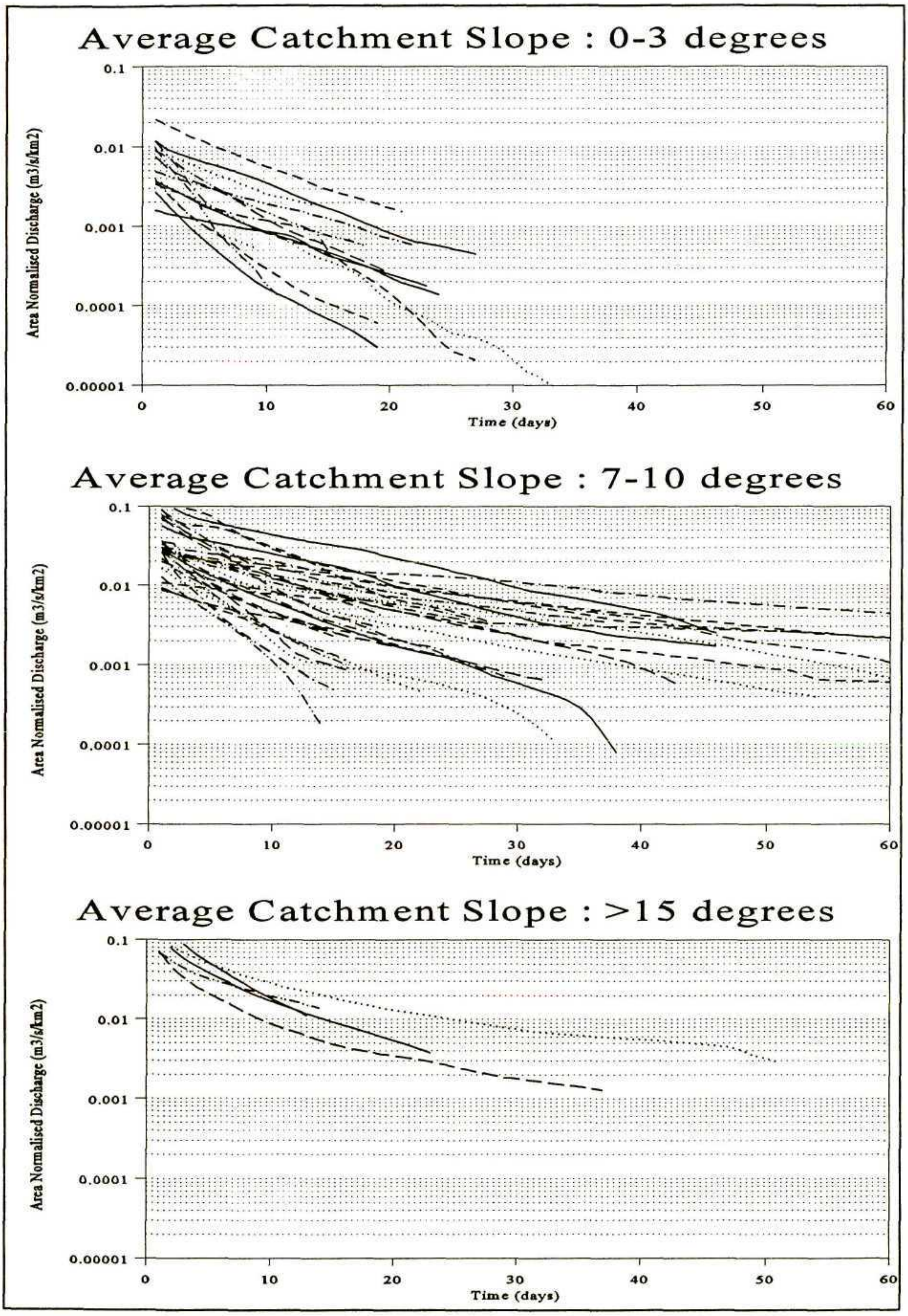


**Appendix 3.7** : MRCs grouped according to catchment morphology



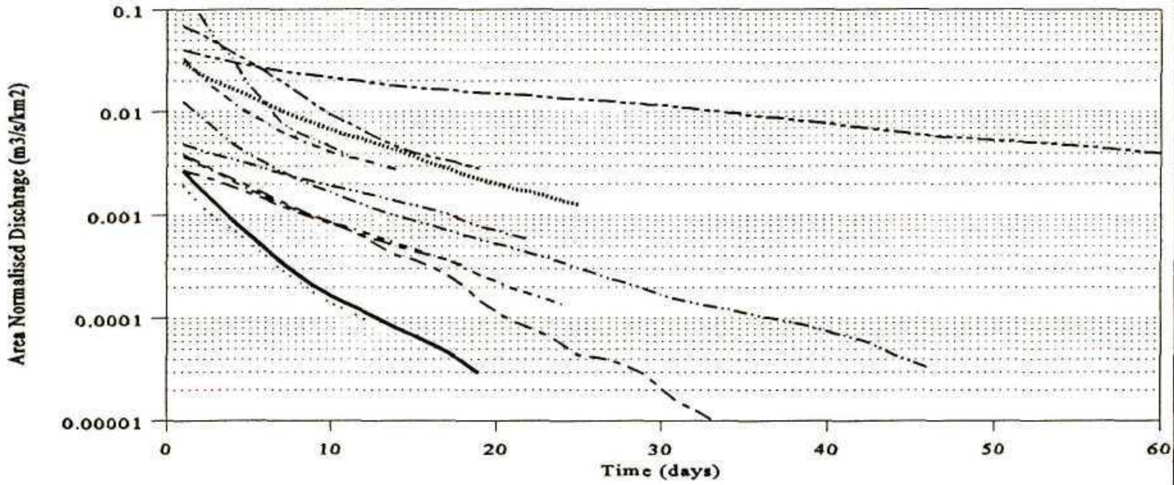



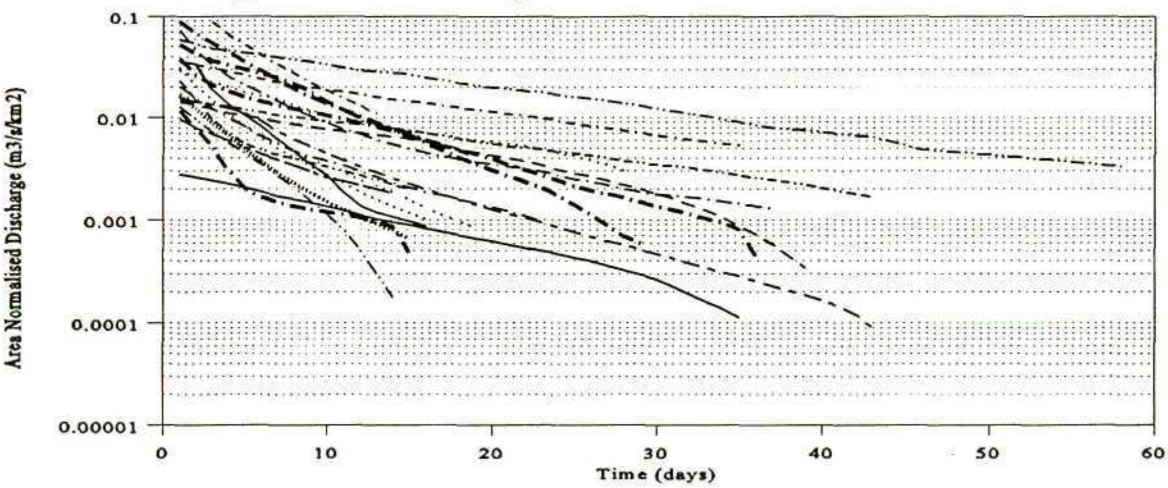


Average Catchment Slope : 0-3 degrees
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Average Catchment Slope : 7-10 degrees
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)
Average Catchment Slope : >15 degrees
Area Normalised Discharge (m3/s/km2)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
Time (days)

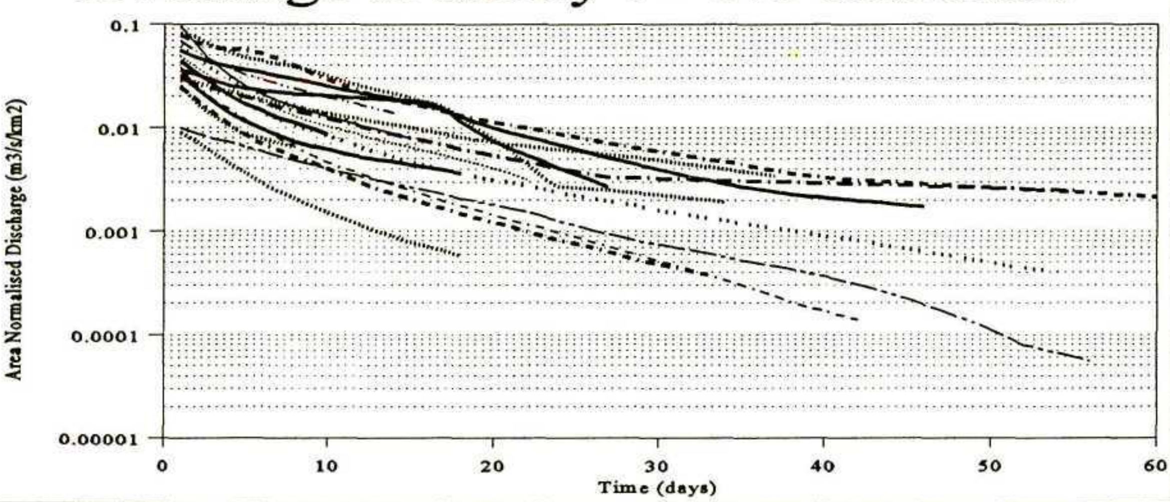
## Drainage Density : <0.1 km/km2



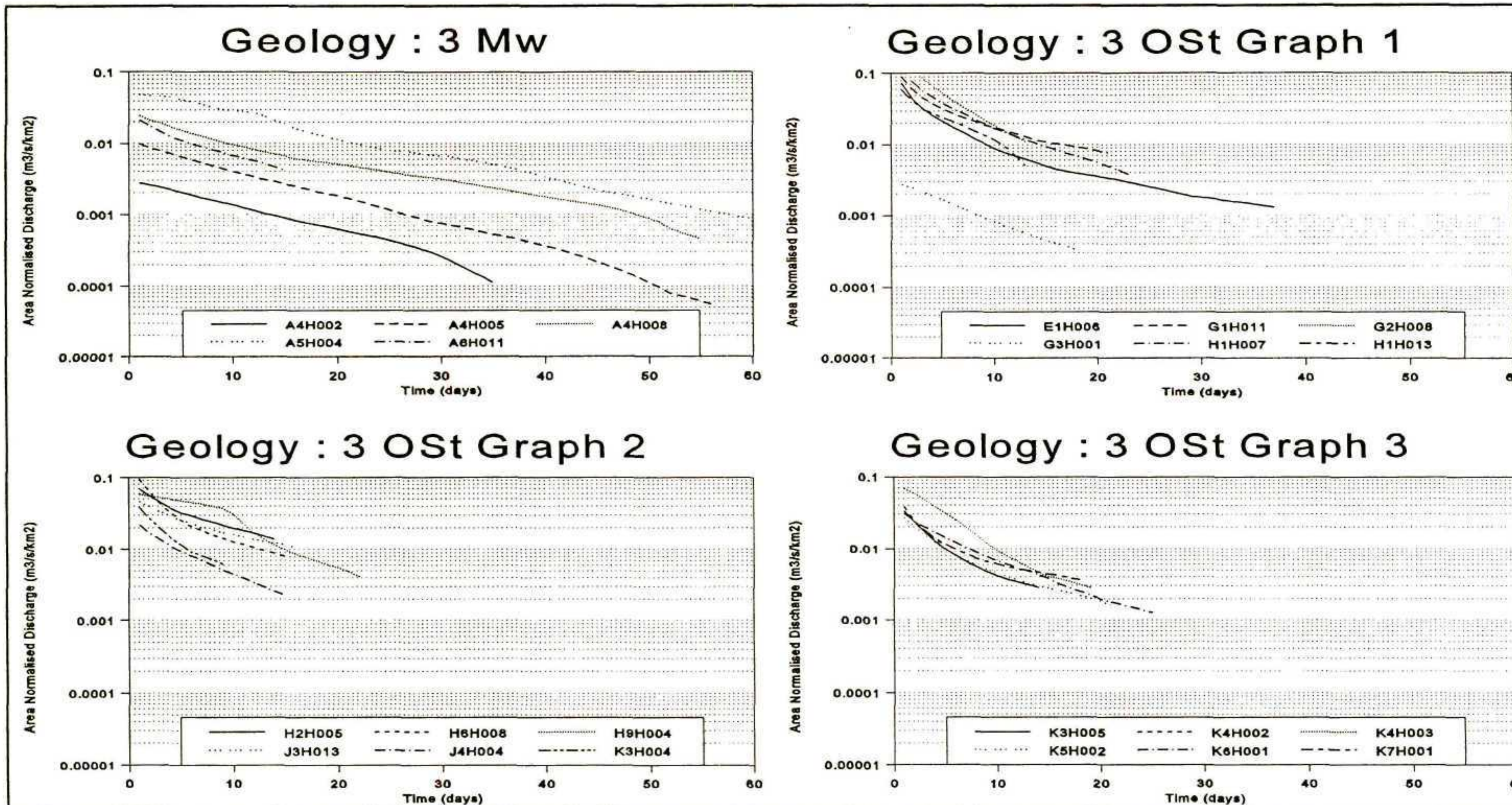

## Drainage Density : 0.1 - 0.5 km/km2

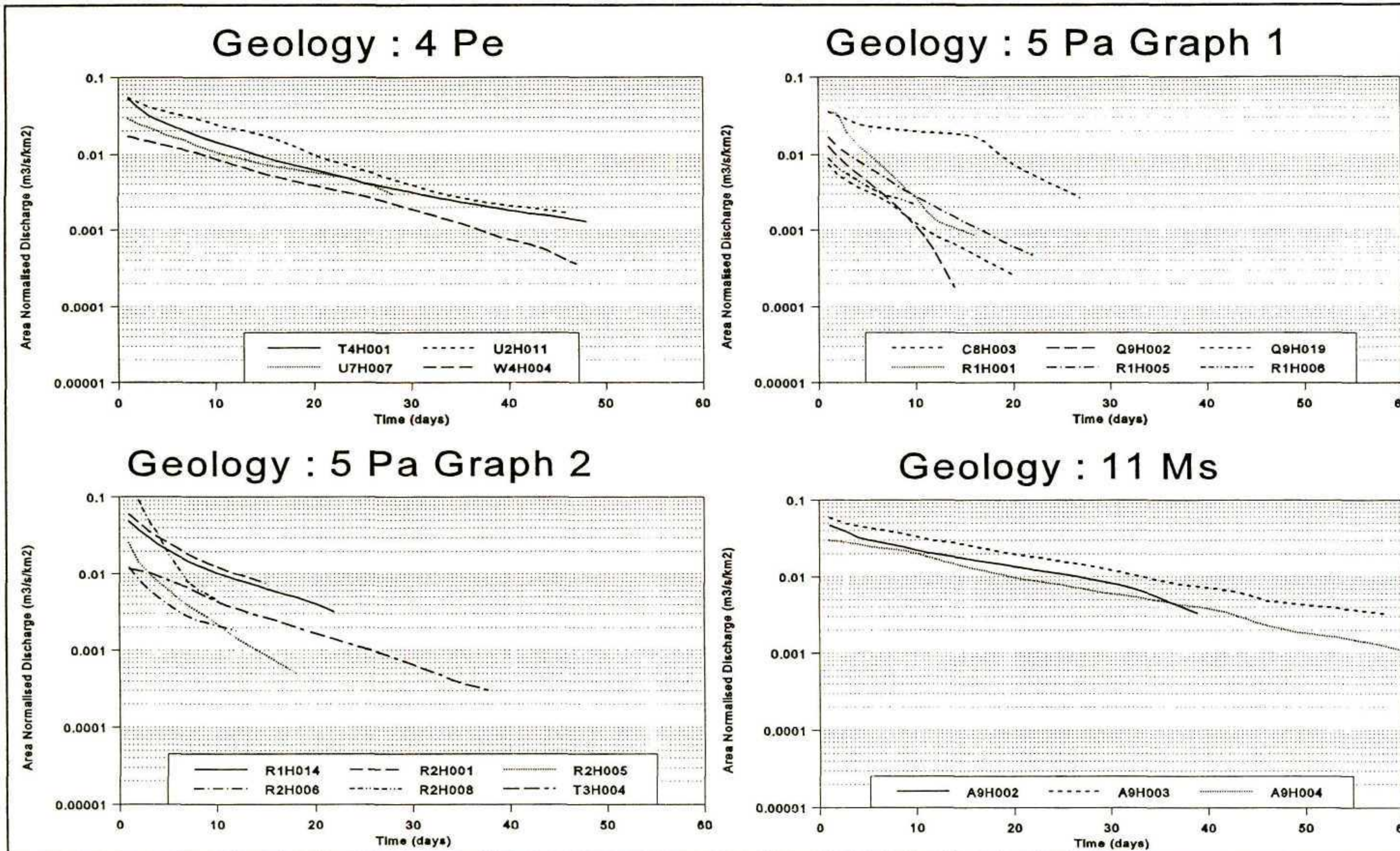



## Drainage Density : >0.5 km/km2



**Appendix 3.8**: Examples of the initial grouping of the MRCs using geology




Geology : 4 Pe
Geology : 5 Pa Graph 1
Geology : 5 Pa Graph 2
Geology : 11 Ms
Area Normalised Discharge (m3/s/km2)
Time (days)
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
50
60
T4H001
U2H011
U7H007
W4H004
C8H003
Q9H002
Q9H019
R1H001
R1H005
R1H006
R1H014
R2H001
R2H005
R2H006
R2H008
T3H004
A9H002
A9H003
A9H004

**Appendix 3.9**: Summary of the half life, log life and initial discharge values for the catchments

| Catchment | Half Life | Log Life | Initial Discharge |
|---|---|---|---|
| A3H001 | 23.0 | 10.3 | 0.0017 |
| A4H002 | 27.7 | 7.2 | 0.0034 |
| A4H005 | 24.6 | 5.9 | 0.0119 |
| A4H008 | 32.1 | 6.0 | 0.0278 |
| A5H004 | 34.7 | 12.6 | 0.0509 |
| A6H011 | 15.3 | 3.5 | 0.0274 |
| A6H012 | 15.1 | 3.2 | 0.0167 |
| A9H002 | 35.2 | 7.8 | 0.0521 |
| A9H003 | 42.7 | 10.6 | 0.0645 |
| A9H004 | 42.9 | 13.1 | 0.0313 |
| B1H001 | 7.3 | 1.7 | 0.0059 |
| B1H004 | 22.1 | 6.6 | 0.0053 |
| B2H001 | 15.6 | 3.9 | 0.0044 |
| B4H005 | 43.0 | 14.0 | 0.0160 |
| B5H002 | 13.3 | 3.8 | 0.0047 |
| B6H001 | 56.7 | 9.4 | 0.0444 |
| B6H002 | 14.1 | 4.4 | 0.1649 |
| B6H003 | 37.1 | 7.5 | 0.0326 |
| B7H004 | 27.6 | 5.9 | 0.1176 |
| B7H008 | 18.0 | 7.4 | 0.0072 |
| B7H010 | 28.1 | 12.6 | 0.0094 |
| C1H007 | 5.8 | 1.8 | 0.0171 |
| C3H003 | 15.7 | 4.7 | 0.0039 |
| C5H012 | 5.2 | 1.8 | 0.0135 |
| C6H003 | 6.2 | 1.5 | 0.0045 |
| C8H003 | 8.2 | 0.8 | 0.0186 |
| C8H012 | 9.1 | 2.2 | 0.0049 |
| E1H006 | 8.5 | 1.6 | 0.1125 |
| E2H002 | 8.9 | 1.9 | 0.0196 |
| G1H003 | 21.6 | 5.1 | 0.1087 |
| G1H007 | 11.2 | 2.8 | 0.1290 |
| G1H011 | 11.7 | 1.6 | 0.1481 |
| G2H008 | 9.7 | 2.6 | 0.2000 |
| G2H012 | 16.1 | 4.5 | 0.0082 |
| G3H001 | 18.1 | 5.5 | 0.0031 |
| G4H006 | 18.1 | 4.7 | 0.0067 |
| G4H014 | 13.3 | 2.5 | 0.0397 |
| G5H008 | 12.6 | 3.4 | 0.0105 |
| H1H007 | 11.4 | 2.3 | 0.1429 |
| H1H013 | 11.8 | 2.5 | 0.0755 |
| H1H018 | 21.0 | 3.7 | 0.1239 |
| H2H001 | 14.2 | 3.0 | 0.0732 |

| Catchment | Half Life | Log Life | Initial Discharge |
|---|---|---|---|
| H2H003 | 12.0 | 5.0 | 0.0404 |
| H2H005 | 14.4 | 3.2 | 0.0867 |
| H4H005 | 10.3 | 2.6 | 0.0583 |
| H6H008 | 8.2 | 1.5 | 0.1579 |
| H7H003 | 5.1 | 1.0 | 0.0533 |
| H9H004 | 19.2 | 10.1 | 0.0600 |
| H9H005 | 6.5 | 1.2 | 0.0570 |
| J2H005 | 13.6 | 4.2 | 0.0198 |
| J3H013 | 16.5 | 3.8 | 0.0586 |
| J3H017 | 15.0 | 2.2 | 0.0086 |
| J4H003 | 8.0 | 1.5 | 0.0632 |
| J4H004 | 12.8 | 2.5 | 0.0303 |
| K3H004 | 9.0 | 1.8 | 0.0588 |
| K3H005 | 8.5 | 1.7 | 0.0513 |
| K4H001 | 9.1 | 1.6 | 0.0360 |
| K4H002 | 5.5 | 1.8 | 0.0545 |
| K4H003 | 10.7 | 3.6 | 0.0833 |
| K5H002 | 11.7 | 2.3 | 0.0376 |
| K6H001 | 14.0 | 2.6 | 0.0424 |
| K7H001 | 11.8 | 1.7 | 0.0526 |
| K8H001 | 8.3 | 1.5 | 0.0429 |
| L8H001 | 12.2 | 2.4 | 0.0857 |
| L8H002 | 11.2 | 2.8 | 0.1154 |
| P4H001 | 10.6 | 2.0 | 0.0365 |
| Q9H002 | 8.1 | 1.9 | 0.0201 |
| Q9H019 | 24.3 | 10.7 | 0.0395 |
| R1H001 | 8.7 | 3.0 | 0.0378 |
| R1H005 | 10.7 | 2.1 | 0.0249 |
| R1H006 | 10.4 | 2.1 | 0.0130 |
| R1H014 | 13.9 | 2.3 | 0.0714 |
| R2H001 | 11.7 | 1.6 | 0.1034 |
| R2H005 | 6.8 | 1.4 | 0.0414 |
| R2H006 | 12.1 | 2.2 | 0.0160 |
| R2H008 | 4.8 | 1.8 | 0.2131 |
| S3H006 | 8.0 | 2.4 | 0.0023 |
| S6H003 | 12.6 | 2.5 | 0.0279 |
| T1H004 | 8.1 | 2.8 | 0.0410 |
| T2H002 | 96.2 | 69.1 | 0.0525 |
| T3H004 | 23.1 | 7.4 | 0.0126 |
| T3H008 | 17.3 | 6.4 | 0.0170 |
| T3H009 | 12.7 | 2.7 | 0.0456 |
| T4H001 | 18.5 | 2.7 | 0.0699 |
| T5H002 | 26.8 | 5.4 | 0.0311 |
| T5H003 | 17.3 | 4.6 | 0.0643 |
| T5H004 | 14.1 | 3.1 | 0.0826 |

| Catchment | Half Life | Log Life | Initial Discharge |
|---|---|---|---|
| U1H006 | 19.2 | 5.2 | 0.0331 |
| U2H001 | 16.9 | 2.1 | 0.0523 |
| U2H006 | 17.2 | 3.6 | 0.0649 |
| U2H007 | 18.8 | 6.4 | 0.0475 |
| U2H011 | 24.1 | 5.7 | 0.0682 |
| U2H012 | 24.9 | 6.9 | 0.0342 |
| U2H013 | 25.6 | 4.8 | 0.0301 |
| U3H002 | 19.6 | 5.6 | 0.0225 |
| U4H002 | 24.5 | 6.5 | 0.0222 |
| U7H007 | 26.9 | 5.2 | 0.0351 |
| V1H001 | 14.2 | 3.4 | 0.0347 |
| V1H002 | 27.3 | 7.1 | 0.0095 |
| V1H009 | 11.1 | 2.0 | 0.0102 |
| V1H038 | 13.3 | 4.3 | 0.0122 |
| V2H001 | 11.9 | 3.3 | 0.0557 |
| V2H005 | 25.9 | 6.9 | 0.0423 |
| V3H002 | 10.1 | 2.4 | 0.0461 |
| V3H003 | 9.0 | 2.0 | 0.0176 |
| V3H005 | 9.7 | 1.9 | 0.0518 |
| V3H007 | 11.5 | 2.9 | 0.0853 |
| V3H009 | 15.7 | 3.9 | 0.0270 |
| V6H003 | 6.6 | 1.2 | 0.0321 |
| V6H004 | 11.3 | 2.3 | 0.0258 |
| V6H006 | 19.5 | 5.3 | 0.0917 |
| V7H012 | 16.1 | 4.6 | 0.0357 |
| V7H016 | 27.5 | 6.6 | 0.0331 |
| V7H017 | 22.4 | 6.5 | 0.0978 |
| W4H004 | 30.0 | 9.3 | 0.0190 |
| W5H004 | 11.9 | 0.9 | 0.0261 |
| W5H006 | 34.1 | 9.2 | 0.0222 |
| W5H008 | 14.3 | 3.1 | 0.0135 |
| X2H005 | 31.2 | 9.7 | 0.0156 |
| X2H008 | 16.0 | 4.8 | 0.0111 |
| X2H010 | 29.1 | 3.8 | 0.0238 |
| X2H011 | 37.4 | 16.2 | 0.0174 |
| X2H012 | 17.1 | 2.0 | 0.0220 |
| X2H013 | 46.2 | 10.8 | 0.0178 |
| X2H014 | 75.1 | 20.3 | 0.0280 |
| X2H015 | 45.0 | 17.7 | 0.0116 |
| X2H022 | 23.6 | 6.7 | 0.0098 |
| X2H027 | 35.3 | 9.7 | 0.0385 |
| X2H031 | 29.0 | 11.5 | 0.0115 |
| X3H001 | 56.1 | 16.6 | 0.0402 |
| X3H003 | 44.5 | 18.3 | 0.0577 |
| X3H006 | 51.5 | 13.8 | 0.0274 |

**Appendix 3.10** : Correlation matrix of the various climatic, morhological, recharge and geological variables

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| HL | 1 | 1.000 | | | | | | | | | | | | |
| SEAS | 2 | 0.208 | 1.000 | | | | | | | | | | | |
| MAP | 3 | 0.195 | 0.128 | 1.000 | | | | | | | | | | |
| CONC | 4 | 0.349 | 0.605 | 0.175 | 1.000 | | | | | | | | | |
| ACRU | 5 | 0.179 | -0.197 | 0.728 | 0.049 | 1.000 | | | | | | | | |
| VEGTER | 6 | 0.495 | 0.108 | 0.680 | 0.302 | 0.656 | 1.000 | | | | | | | |
| AREA | 7 | -0.084 | 0.084 | -0.193 | 0.181 | -0.241 | -0.197 | 1.000 | | | | | | |
| SLOPE | 8 | -0.051 | -0.419 | 0.452 | -0.370 | 0.601 | 0.164 | -0.241 | 1.000 | | | | | |
| DD | 9 | 0.028 | 0.118 | 0.031 | -0.064 | -0.026 | -0.050 | -0.046 | 0.114 | 1.000 | | | | |
| LL | 10 | 0.853 | 0.178 | 0.079 | 0.222 | 0.049 | 0.265 | -0.032 | -0.069 | 0.056 | 1.000 | | | |
| Q0 | 11 | -0.152 | -0.183 | 0.535 | -0.173 | 0.578 | 0.235 | -0.222 | 0.600 | 0.003 | -0.110 | 1.000 | | |
| GEOL | 12 | 0.401 | 0.093 | -0.091 | 0.286 | -0.162 | 0.106 | -0.013 | -0.153 | -0.021 | 0.215 | -0.184 | 1.000 | |
| DUR | 13 | 0.661 | 0.26 | 0.192 | 0.475 | 0.285 | 0.471 | 0.059 | -0.077 | -0.005 | 0.352 | -0.057 | 0.4 | 1.00 |
| | | | | | | | | | | | | | | |
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |

HL Half Life
SEAS Rainfall Seasonality
MAP Mean Annual Precipitation
CONC Rainfall Concentration
ACRU ACRU Simulated Recharge
VEGTER Recharge as Estimated by Vegter (1995)
AREA Catchment Area
SLOPE Average Catchment Slope
DD Drainage Density
LL Log Life
Q0 Initial Discharge
GEOL Geological Index
DUR Recession Duration