Assessment of Groundwater Availability from Recession Flows and Instream Flow Requirements of Rivers in South Africa

Report to the
Water Research Commission

by

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WRC Report No. KV 339/15
ISBN 978-1-4312-0677-3

May 2015

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The publication of this report emanates from a project entitled *Assessment of Groundwater Availability from Recession Flows and Instream Flow Requirements of Rivers in South Africa* (WRC Project No. K8/1049).

Abstract

Groundwater is an important resource for multiple uses in South Africa. However, setting limits to its sustainable abstraction while assuring basic human needs is a must. Due to prevalent data scarcity related to groundwater replenishment, which is the traditional basis for estimating groundwater availability, the present report presents a novel method for determining allocatable groundwater in quaternary catchment through information on streamflows. Using established methodologies for assessing baseflows, recession flows, and instream ecological flow requirements, the methodology develops a combined stepwise methodology to determine annual groundwater storage volumes in the catchments using linear reservoir theory, essentially linking low flows proportionally to upstream groundwater storages.

The approach was trialled for twenty-one perennial and relatively undisturbed quaternary catchments with long-term and good streamflow records. Using the Desktop Reserve Model to estimate instream ecological flow requirements of the streams and equating these with ecological groundwater reserve, excess baseflows were converted into groundwater storages on an annual basis. Results show that groundwater development potential exists in nineteen of the catchments, with upper limits to allocatable groundwater volumes ranging from 0.01 to 1.58 MCM/yr over the catchments. With a secured availability of these volumes 75% of the years, variability between years is assumed to be manageable. A significant (R^2 = 0.86) correlation between baseflow index and the drainage time scale for the catchments underscored the physical basis of the methodology and also enables the reduction of the procedure by one step, omitting recession flow analysis. The method serves as an important complementary tool for the assessment of the groundwater part of the Reserve and the groundwater directed measures.

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Acronyms and Abbreviations

BBM	Building Block Methodology
BFI	BaseFlow Index
BHN	Basic Human Needs
CV index	An index of streamflow variability based on coefficients of variations
CVB	A combined hydrological index of flow variability calculated from CV index/BFI
DEM	Digital Elevation Model
DRM	Desktop Reserve Model
DWA	Department of Water Affairs, South Africa
DWAF	Department of Water Affairs and Forestry, South Africa
Ecological reserve	Instream flow requirements in South Africa
GRDM	Groundwater resource directed measure
GWallocate	Upper limit of groundwater allocation
GWBF	Groundwater contribution to baseflow
IFR	Instream Flow Requirement
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MLIFR	Maintenance low instream flow requirement, based on BBM
NFEPA	National Freshwater Ecosystems Priority Areas
NWA	National Water Act of South Africa
PES	Present ecological state
PART	A computerized method for baseflow record estimation
RDM	Resource Directed Measure
SRTM	Shuttle Radar Topographic Mission remote sensed digital elevation model data

1. Introduction

According to the National Water Act of South Africa (NWA, Act 36 of 1998), water-use licensing, including to groundwater, is to be granted only after defining and fulfilling the Reserve, the amount of water needed to supply basic human needs (BHN) and preserve ecological integrity (Xu et al., 2003). The objective of the NWA is to keep water, including groundwater, development within sustainable limits, while also adhering to efficiency and equity goals. In order to allocate water in accordance with the requirements of the NWA it is imperative that the interdependencies between groundwater and surface water are realized and incorporated into the assessments and allocations of each resource (Kelbe and Germishuyse, 2010). Quantification of the 'groundwater component of the reserve', i.e. the groundwater needed to fulfil BHN and ecological needs, is very important for the successful implementation of the NWA. However, estimating groundwater volumes and fluxes is a major challenge in South Africa due to large hydrogeological variability and complexity and limited groundwater data (Levy and Xu, 2012).

Acknowledging these facts, the generally accepted method for estimating the groundwater quantity part of the Reserve, as an element of defining the so-called groundwater resource directed measures (GRDM)[1] of the NWA, is to use estimates of groundwater recharge and stream baseflow as the upper limit for groundwater exploitation and the upper requirements for groundwater discharge to streams, respectively. According to Parsons and Wentzel (2007), the relationship to be solved is

$$GWallocate = (Re + GWin - GWout) – BHN - GWBf \quad (1)$$

Where: GWallocate = upper limit for groundwater allocation

Re = groundwater recharge from rainfall

GWin = groundwater inflow (normally disregarded)

GWout = groundwater outflow (normally disregarded)

BHN = basic human needs

GWBF = groundwater contribution to baseflow

This relationship has an aquifer or a hydrological unit as the base, normally the fourth-order (quaternary) catchments delineated for South Africa (Parsons and Wentzel, 2007) and evaluates fluxes on an annual scale. Baseflow is that fraction of stream discharge that is not attributable to direct runoff from precipitation or melting snow. It is sustained on a more continuous basis, even under dry conditions, principally by groundwater discharge. As such, groundwater is critical in sustaining ecological functioning of most streams. GWBF is here the minimum amount of groundwater discharge required to sustain the ecological integrity of groundwater dependent

[1] Groundwater Directed Measures (GRDM) comprise three components: Classification, the Reserve and Resource Quality Objectives. The terms RDM and the Reserve are often used interchangeably, which is incorrect. RDM refers to one of the strategies adopted to implement the National Water Act and includes Classification, the Reserve and Resource Quality Objectives. The Reserve is just one part of RDM, and specifically refers to the quantity and quality of water required to meet basic human needs and those of aquatic ecosystems (Parsons and Wentzel, 2007).

systems, like rivers, wetlands, and lakes) (Levy and Xu, 2012). BHN is the part of the Reserve that caters for a minimum of water supply for human uses (e.g., 25 L/d/capita). The total Reserve is the sum of BHN and GWBF. Any new development and allocation of groundwater (GW allocate) has to be met from the possibly remaining surplus, which is the difference between the recharge and the total Reserve. The most uncertain parameters in this assessment are the recharge (Re) and the groundwater-derived minimum baseflow (GWBF). The application of this method is exemplified in Dennis et al. (2012).

An alternative approach, which is applied and exemplified in this study, is based on the premise that the baseflow component of streamflow in unregulated basins is a good indicator of groundwater storage and availability in the basin. Groundwater abstraction or factors impacting groundwater recharge will alter the groundwater storage and consequently the natural baseflow regime. Hence, it is assumed that the amount of water that is available for new groundwater development for use like BHN, agriculture and industry in a catchment, is the baseflow that is in excess of an 'environmental baseflow requirements'. In order to relate baseflow to groundwater storage, recession flow analysis is applied. Assuming that the recession flows, in the absence of precipitation and direct surface runoff, consist of the cumulative outflow from all upstream phreatic aquifers representing a linear reservoir, the analysis of these flows can infer information on storage of groundwater in these aquifers through a proportionality factor, the drainage time scale (Brutsaert and Sugita, 2008). Similarly, the 'river ecological reserve' or instream flow requirements, when less than river baseflow, can be converted to a groundwater storage in the catchment necessary to maintain them, constituting part of the 'groundwater ecological reserve'. By analogy, any baseflow in excess of this instream flow requirement represents, when converted to a groundwater storage, the groundwater volume allocatable to all human uses, including BHN.

The study proposes to apply this approach for the first time in South Africa as part of the determination of the Reserve and the RDMs. The approach was initially proposed by Smakhtin (2001) and has recently been trialled in Africa, more specifically a catchment in Tanzania (Shu and Villholth, 2013).

The overall aim of the project is to contribute to an improved assessment of the groundwater component of the Reserve at the quaternary catchment level, as sought after in Parson and Wentzel (2007), as part of establishing groundwater resource directed measures (GRDMs) for protection and sustainable development of water resources as well as supporting the development of guidelines for allocation of groundwater resources. The rest of this report is organized as follows. The second section contains relevant background information and describes the approach and the data used. The third section presents the results, while the fourth section discusses the results and findings. Finally, the fifth section presents the main conclusions of the study

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2. Materials and Methods

The determination of groundwater reserve and allocatable groundwater follows the methodology presented in Figure 1.

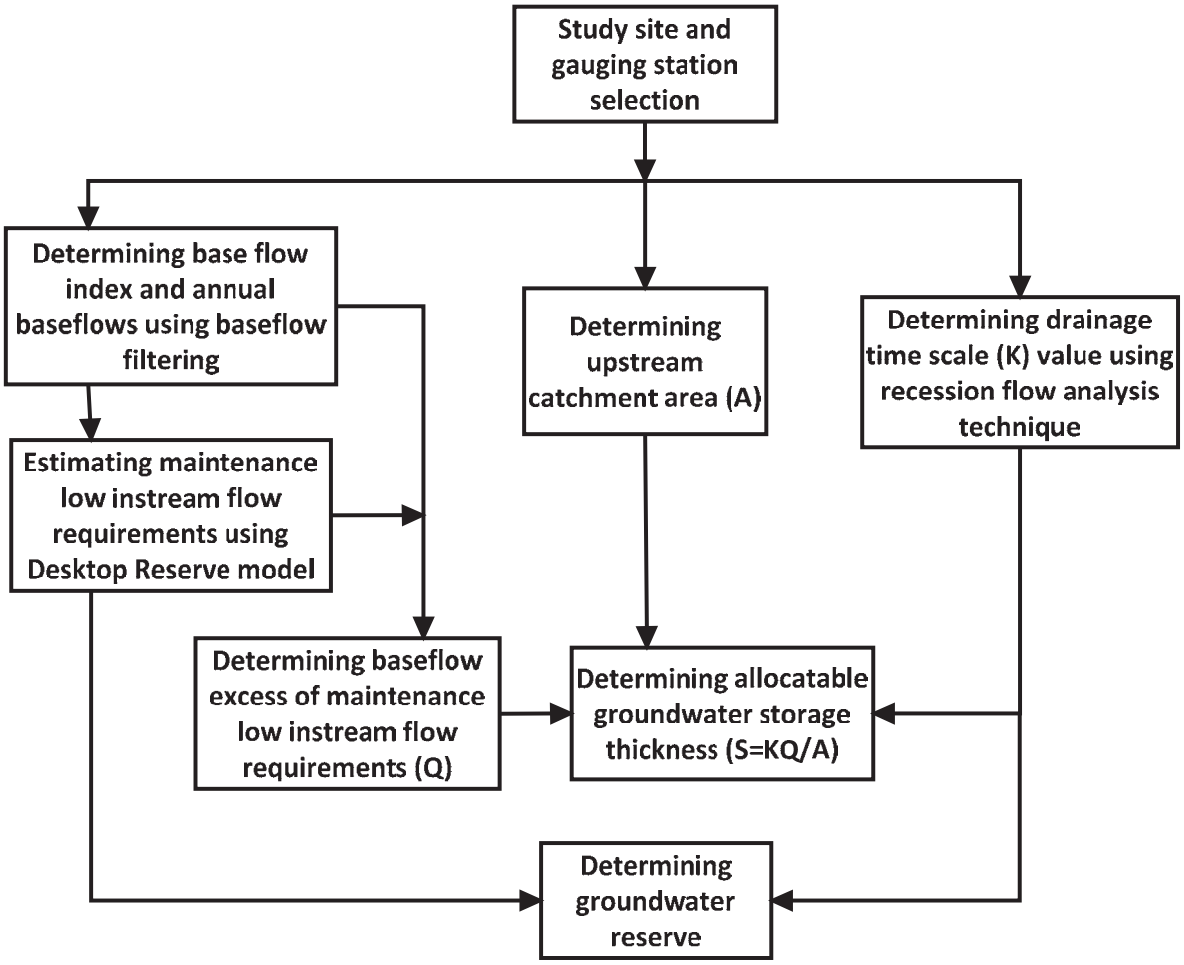

Figure 1: Flow chart showing the methodology for determining groundwater reserve and allocatable groundwater

The methodology consists of the following seven steps:

1. Find long (> 30 years) streamflow records of perennial rivers in quaternary catchments
2. Determine the river baseflows through a baseflow separation method
3. Determine any temporal trends of the baseflow records
4. Determine the drainage time scale K from the recession parts of the stream flow records
5. Determine the ecological flow requirements in the rivers for predetermined ecological status, based on the desktop model for estimating ecological instream flow requirements (Hughes and Hannart (2003)
6. Determine the river baseflow surplus after subtracting from the baseflow the instream flow requirements
7. Convert the river baseflow and the baseflow surplus to groundwater storage equivalents using the drainage time scale, yielding the groundwater ecological reserve and the upper limit for groundwater abstraction for all human uses in the catchment, respectively

The analysis is based on a daily temporal resolution for the baseflow separation and the recession flow analysis, while the instream flow requirements and groundwater availability is based on an annual scale.

2.1 Selection of study sites and gauging stations

Daily streamflow data were obtained from the Department of Water Affairs (DWA) online data archive (http://www.dwaf.gov.za/Hydrology/hymain.aspx). The DWA online data archive reports information on streamflow across the nation for approximately 1220 gauging stations.

For the present study, river gauging stations suitable for recession flow analysis and groundwater reserve estimation were selected based on a number of criteria. The selection was done in two steps. The first step was carried out by looking at the spatial map of all the gauging stations in conjunction with other maps (e.g. dams, cities, quaternary catchment map, google maps). The second step was carried out looking at the online data archive metadata and streamflow time series themselves. The first step selection criteria include:

(i) **Catchment size**: The size of the catchment cannot be too small or too large. Small catchments may have very localized features, which will significantly influence the recession flow characteristics at the outlet of the catchment. Conversely, large catchments may not represent well the groundwater processes and the conditions may vary substantially across the catchment. Furthermore, there will be a significant lag time between upstream and downstream processes. To identify catchments of intermediate size, only river gauges in quaternary catchments were chosen.

(ii) **Perennial rivers**: in recession flow analysis, we are interested in recession flows resulting from groundwater storage outflow, which occur during dry periods without direct surface runoff. Hence, rivers suitable for recession flow analysis should obtain part of their flow from groundwater discharge during no rainfall periods or should be perennial rivers. Using Hughes et al. (2007) baseflow index (BFI) map, potential gauging stations were selected from regions with relatively high baseflow index (BFI>0.25) to enhance the chance that the selected rivers have a significant groundwater discharge component.

(iii) **Minimum human impact:** Rivers should be relatively pristine in nature with minimum human impact or regulation. Following the Gustard et al. (1992) and Eng and Milly (2007) methodology, stations used for recession analysis should be free from: artificial or lined channels, and should not drain more than 25% of the gauged basin through a dam. We ensured that the selected basins are at natural conditions or have minimum impact due to human activities by selecting gauging stations in catchments which do not contain large water resources schemes or regulation structures such as dams visible from Google Maps. This was done by overlying the GIS maps of dams and other large water resources structures, like irrigation, with the quaternary catchment map. Canalisation is most evident in densely populated urban areas in South Africa. Hence, rivers suffering from canalisation or presence of diversion weirs were excluded by excluding catchments with large urban areas. Quaternary catchments complying with these criteria were assumed to be unregulated for the purpose of this study.

Based on the above first three selection criteria, 57 river gauging stations distributed across the country were identified as potentially suitable (Annex 1, Figure 16). These quaternary catchments

range in size from 16-42,472 km^2 (Annex 1), and their locations covered a wide range of geology, climate as well as topography. Further, in the second step, screening was carried out using the following six criteria

(i) No missing information (meta data) on the online archive (e.g. catchment area)
(ii) Availability of long-term (more than 30 years) daily streamflow data
(iii) No large time series gaps (discontinuities in time series)
(iv) No flow records with zero flow (i.e. rivers are perennial)
(v) No obvious visual long-term trends in stream flow records (which could be a sign of abstraction and diversion)
(vi) Percentage of missing data not more than 10%.

Using the above six screening criteria, 21 gauging stations were identified for further analysis among the 57 potential gauging stations. The drainage area of these quaternary catchments ranges in size from 22-696 km^2, according to the online archive. The selected 21 gauging stations are presented in Table 1, and their corresponding spatial locations are shown in Figure 2. The long-term mean monthly rainfall for rainfall stations in and around the selected quaternary catchments is shown in Figure 3.

Table 1: Selected 21 gauging stations with their coordinates, period of record, and drainage area and location of rainfall stations in or around the selected catchments

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)[a]	Rainfall Station	Location	Latitude	Longitude	MAP[b] (mm)
B81D	B8H010	Letsitele River @ Mohlabas Location	-23.8932	30.35771	1960-present	477	K2E001	Voorburg @ Wolwedans Dam	-34.01444	22.23083	655
A42D	A4H008	Sterkstroom @ Doornspruit	-24.2169	27.9733	1964-present	504		Ronde Valley @ Rondevlei	-33.96677	22.72033	634
B73A	B7H004	Mohlolobe	-24.5562	31.03225	1950-present	136		Midmar @ Midmar Dam	-29.49332	30.19797	859
B42F	B4H005	Waterval River @ Modderspruit	-25.0359	30.21942	1960-present	188	B4E003	Buffelskloof @ Buffelskloof Dam	-24.95828	30.26367	669
B11K	B1H004	Klipspruit @ Zaaihoek	-25.6736	29.17322	1959-present	376	U2E003	Groendraai	-24.19234	27.96220	528
C81F	C8H005	Elands River @ Elands River Drift	-28.3758	28.86028	1963-present	696	K3E003	Letsitele	-23.86737	30.42894	526
V60A	V6H004	Sondags River @ Kleinfontein	-28.4049	30.0128	1954-present	658	B6E003	Blyderiv.Poortnatres @ Blyderiv.Poort Dam	-24.53744	30.79738	638
U20D	U2H006	Karkloof River @ Shafton	-29.3818	30.27775	1954-present	339	C8E009	Many Waters @ Sterkfontein Dam	-28.43791	28.97083	604
U20B	U2H007	Lions River@(Mpofana River) @ Weltevreden	-29.4426	30.14853	1954-2013	358	U6E002	Salem @ Shongweni Dam C.Are	-29.867	30.7331	710

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)	Rainfall Station	Location	Latitude	Longitude	MAP (mm)
U20A	U2H013	Mgeni River @ Petrus Stroom	-29.5126	30.09442	1960-present	299	B3E003	Loskop Nat. Res. @ Loskop Dam	-25.42143	29.35807	663
U70A	U7H007	Lovu River @ Beaulieu Estate	-29.8624	30.24417	1964-present		V1E005	Van Reenen	-28.36619	29.37836	1058
K80C	K8H001	Kruis River @ Farm 508	-33.9819	24.02097	1961-present	26	K3E003	Ronde Valley @ Rondevlei	-33.99177	22.72033	741
K80C	K8H002	Elands River @ Kwaai Brand For. Re	-33.9814	24.05014	1961-present	35	B1E004	Rietfontein Rietfontein	-26.35776	26.35776 29.2164	722 29.2164
K70B	K7H001	Bloukrans River @ Lotterings For.	-33.9556	23.6386	1961-present	57					
K60A	K6H001	Keurbooms River @ M'Kama	-33.8036	23.13528	1961-present	165					
K50A	K5H002	Knysna River @ Milwood Forest R	-33.8911	23.02944	1961-present	133					
K40B	K4H001	Hoekraal River @ Eastbrook	-33.9798	22.7995	1959-1993	111					
K40C	K4H002	Karatara River @ Karatara Forest Res.	-33.88083	22.83778	1961-present	22					
K30D	K3H005	Touws River @ Farm 162	-33.9453	22.61444	1969-present	78					
K30A	K3H003	Maalgate River @ Knoetze Kama	-34.0067	22.35028	1961-present	145					
K20A	K2H002	Great-Brak River @ Wolvedans	-34.0286	22.22194	1961-present	131					

[a] Data from the DWA online archive, [b] Mean Annual Precipitation

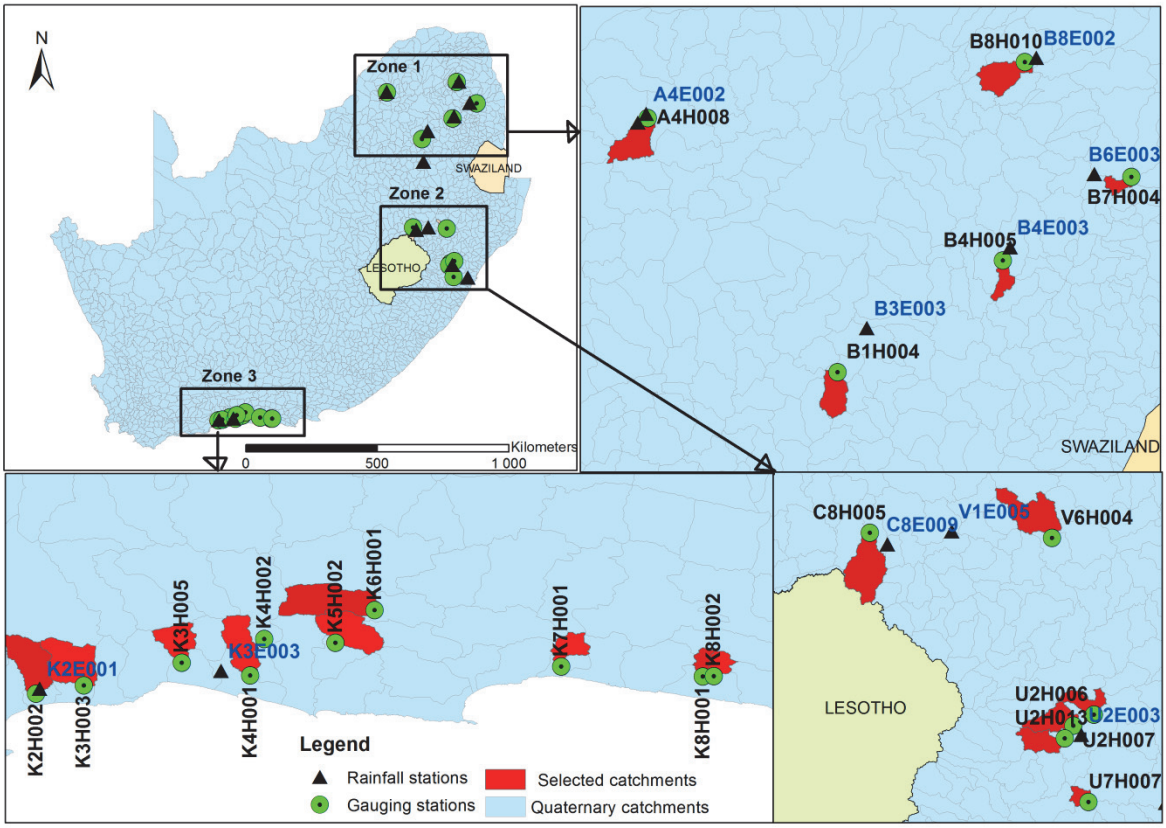

Figure 2: Map of finally selected river gauging stations (21 in total, black labels) and rainfall stations

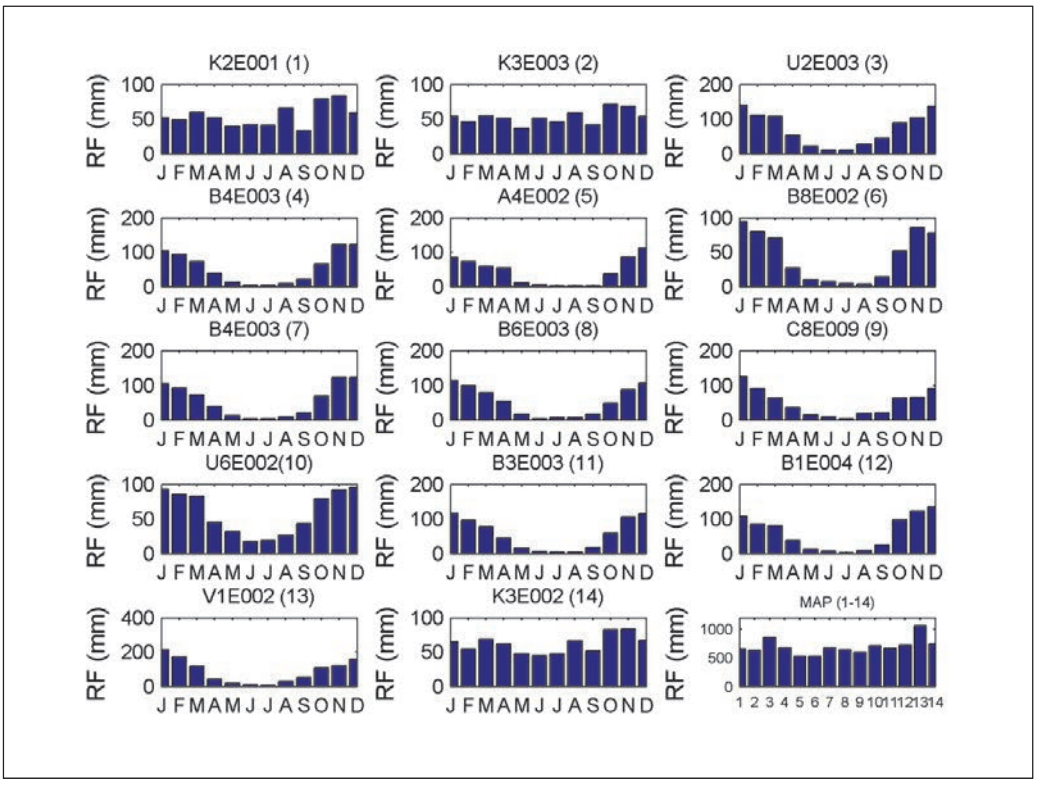

Figure 3: Long-term mean monthly rainfall for rainfall stations in and around the quaternary catchments (the last plot shows the mean annual precipitation for all rainfall stations (1-14))

2.2 Catchment area delineation

Ten out of the twenty-one quaternary catchments (B42F, K50A, K30D, K20A, K80C, K30A K70B, K80C, C81F, and K40C) do not have river gauging stations at the catchment outlet. Therefore, we carried out drainage area delineation for all quaternary catchments for areas upstream of the stream gauge, including those with the river gauging station at the catchment outlet. This was done in order to keep consistency in results presentation. To delineate the catchments, 90m X 90m Shuttle Radar Topographic Mission (SRTM) remote sensing digital elevation model (DEM) datasets were downloaded freely from U.S. Geological Survey website (http://earthexplorer.usgs.gov/). The SRTM dataset downloaded for this study is void-filled, i.e. corrected for topographical sink errors in the data. Catchment area delineation was carried out using ArcGIS environment. Figure 4 shows the catchment area of seven catchments, which have river gauging station located far upstream of the catchment outlet. The elevation of the quaternary catchments ranges from -1.4 m to 2323m above mean sea level, measured as average over each catchment from the raster DEM. Table 2 presents the area of the twenty-one quaternary catchments, ranging from 33 to 851 km^2. The catchment area delineated in the present study is slightly higher than catchment area reported in the online archive; at least for quaternary catchments with river gauging station at the catchment boundary. This could be because the quaternary catchment area reported was not delineated using total upstream drainage contribution to the particular gauging station.

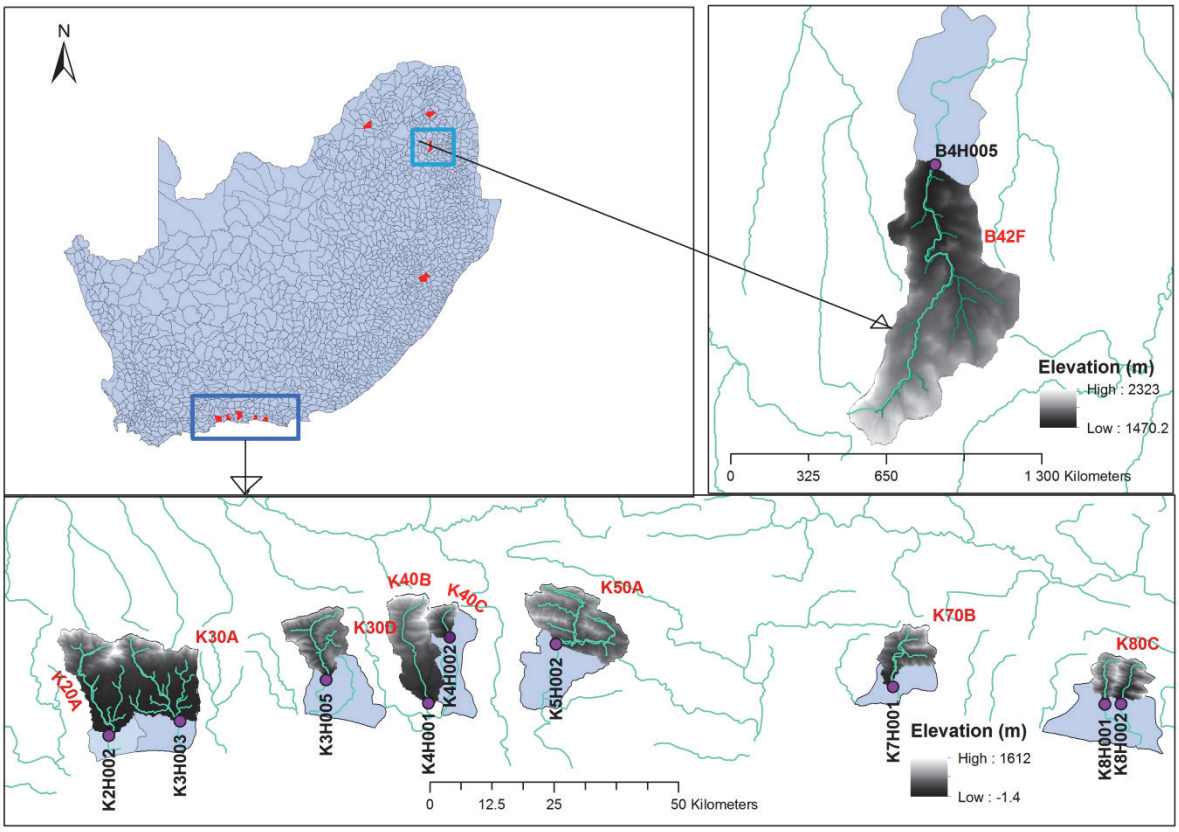

Figure 4: Delineated watersheds, selected 10 catchments which do not have river gauge at the catchment outlet, out of the 21 quaternary catchments

Table 2: Upstream catchment areas for the gauging stations

Catchment ID	Gauging station	Upstream Catchment area (km^2)	Catchment ID	Gauging station	Upstream Catchment area (km^2)
B81D	B8H010	565	K80C	K8H001	38
A42D	A4H008	597	K80C	K8H002	51
B73A	B7H004	163	K70A	K7H001	83
B42F	B4H005	232	K60A	K6H001	267
B11K	B1H004	464	K50A	K5H002	194
C81F	C8H005	902	K40B	K4H001	162
V60A	V6H004	851	K40C	K4H002	33
U20D	U2H006	318	K30D	K3H005	113
U20B	U2H007	466	K30A	K3H003	211
U20A	U2H013	391	K20A	K2H002	189
U70A	U7H007	151			

2.3 Estimating drainage time scale from recession flow analysis

Recession flow analysis for the twenty-one gauges was carried out following the methodology originally proposed by Brutsaert and Nieber (1977). The Boussinesq equation describing flow in unconfined aquifers based on the hydraulic approach is shown in Brutsaert and Nieber (1977) to be expressed in general as a power law function:

$$\frac{dQ}{dt} = -aQ^b \tag{2}$$

Where Q (L^3/T) is the river discharge during recession, $(-\frac{dQ}{dt})$ is rate of change of discharge, a (-) and b (-)are parameters.

By linearizing the Boussinesq equation and retaining the fundamental harmonic in the Fourier expansion to describe outflow from a rectangular aquifer into an empty channel, the constant in equation 2 can be shown to be (Brutsaert and Lopez, 1998):

b=1 (3)

$$a = \frac{\pi^2 k_o pDL^2}{fA^2} \tag{4}$$

Where k_o is the hydraulic conductivity, f is the drainable porosity, D is the aquifer thickness, L is the total of upstream channels in the watershed, and A is the drainage area of the catchment. Drainable porosity is the pore volume of water that is removed (or added) when the water table is lowered (or raised) in response to gravity and in the absence of evaporation[2]. According to Brutsaert and Lopez (1998), the parameter p is a constant (introduced to compensate for the approximation resulting from linearization), which can be estimated to be 0.346. On the other hand, Brutsaert (2008) called p

[2] http://nrcca.cals.cornell.edu/soil/CA2/CA0212.5.php

as an empirical weighting constant whose value range between 0.3 and 0.1 or smaller as the water table declines in the range of lowest flows.

Basically, a in equation (4) is the inverse of the drainage time scale (K) given by (Brutsaert, 2008):

$$K = \frac{0.1f}{\mathrm{D_d}^2 \mathrm{T_e}} \tag{5}$$

Where D_d is the drainage density given by (L/A), and T_e is the effective hydraulic transmissivity of the aquifer and is given by $T_e=k_opD$.

Brutsaert and Lopez (1998) and Brutsaert (2008) have shown that the behaviour of hydrograph recession during low flow is best described with Equation 2 using a value of b=1. The flow recession in this case approximates an exponential decay function and the storage-discharge relationship behaves as a linear reservoir, which can be expressed using Equation 6:

$S = KQ$ =Q/a (6)

Where S is the aquifer storage (L^3), Q is the recession flow (L^3/T), a is the recession constant, and K (=1/a) (T) is the characteristic drainage time scale.

Groundwater storage estimaton using Equation 6 requires prior estimation of the drainage time scale or the recession constant. However, in practice, it is diffult to obatian the value of a using Equation 4 or K using Equation 5. Instead, its value is inferred from streamflow observations. From Equation 2 and assuming a linear reservoir approximation:

$$\log(-\frac{dQ}{dt}) = \log(a) + \log(\mathrm{Q}) \tag{7}$$

When daily values of -dQ/dt and Q are plotted on log-log graph, the cluster of the points is 'enveloped' by a lower line of slope equal to 1 (Figure 5). The envelope line represents the lowest recession rate (-dQ/dt) for a given Q, which is considered the baseflow condtion. One advantage of this method is that it eliminates the problem of determining the time reference t=0 after each interruption of baseflow recession by precipitation (Brutsaert and Nieber, 1977; Zecharias and Brutsaert, 1988). The log-log graph is used because ($-\frac{\mathrm{dQ}}{\mathrm{dt}}$) and Q both typically span several orders of magnitudes and their relationship to one another can best be viewed on log-log plots (Troch et al., 2013). Furthermore, for the linear reservoir assumption (b=1), the slope is equal to one.

Measurement errors, especially for low flows close to zero are most common and reported by many researchers as an unavoidable error in recession analyses. To overcome this problem, it is recommended to establish the lower envelope by roughly keeping 5% of the data below the line (Brutsaert, 2008; Brutsaert and Hiyama, 2012). Lyon et al. (2014) assumed 15% of the data points to lie below the line. In another study, Mendoza et al. (2003) allowed 10% of the data points below the line that define the lower envelope curve. Figure 5 shows an example of a lower envelope line plotted by keeping 5% of the data points below the line.

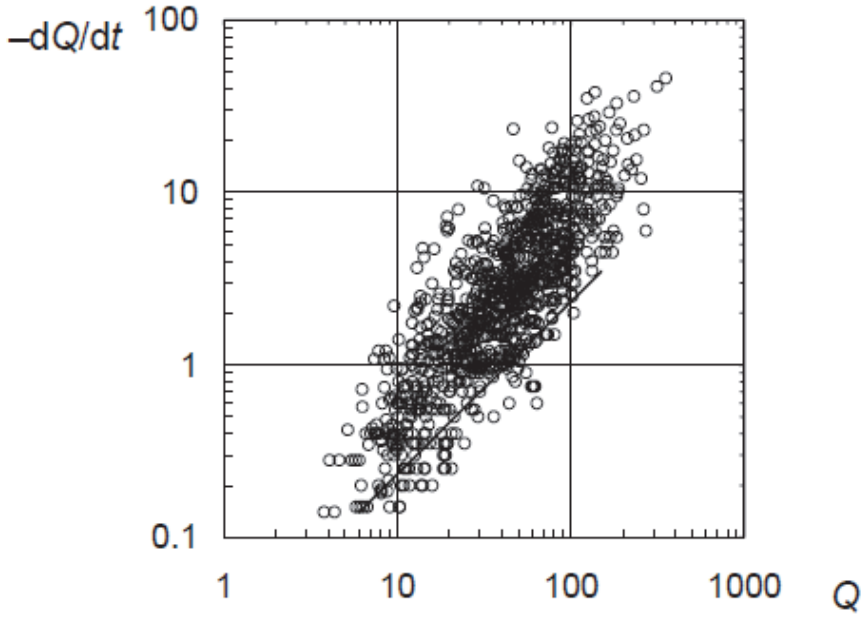

Figure 5: Example of lower envelop line with a unit slope plotted by keeping about 5% of the data points below the line. The data points -dQ/dt and Q represent the hydrograph recession of Kherlen River, Undurkhaan, Mongolia (source: Brutsaert and Sugita (2008))

In recession analysis, concurrent daily rainfall data can be used to eliminate streamflow points during and immediately following precipitation. However, this approach may induce uncertainties especially when applied to large river basins due to the fact that the rain gauge network density will never be sufficient to capture all events everywhere in the basin (Brutsaert, 2008). In the absence of concurrent precipitation data, which is the case in this study, we followed Brutsaert and Sugita (2008) approach to maximize the chance of selecting flow points that are a result of recession flows:

(i) All streamflow that have positive or zero dQ/dt values have been removed
(ii) –dQ/dt values that have double or larger values than the previous ones were considered to be anomalous and eliminated
(iii) Two data points before dQ/dt becomes positive or zero were removed
(iv) Three data points after major events were eliminated

Before applying the above procedure, years with missing data were identified and the entire year was considered missing following Brutsaert (2008) approach. Following Stoelzle et al. (2013) major events in this study was defined as streamflow values greater than 30% exceedance frequency during the period of record. We wrote a MATLAB function and automated the recession flow analysis of long time series of daily streamflow data. Figure 6 shows the extracted recession flow data points and the total streamflow for one of the gauging stations during a window of the full record. Figure 7 shows the log-log plot of - dQ/dt vs Q for the same station. We determined drainage time scale (K) by fitting a straight line with a unit slope to the double logarithmic plot by keeping

roughly 10% of the data points below the line (Figure 7). The 10 % limit was decided by looking at the quality codes of the streamflow measurements[3].

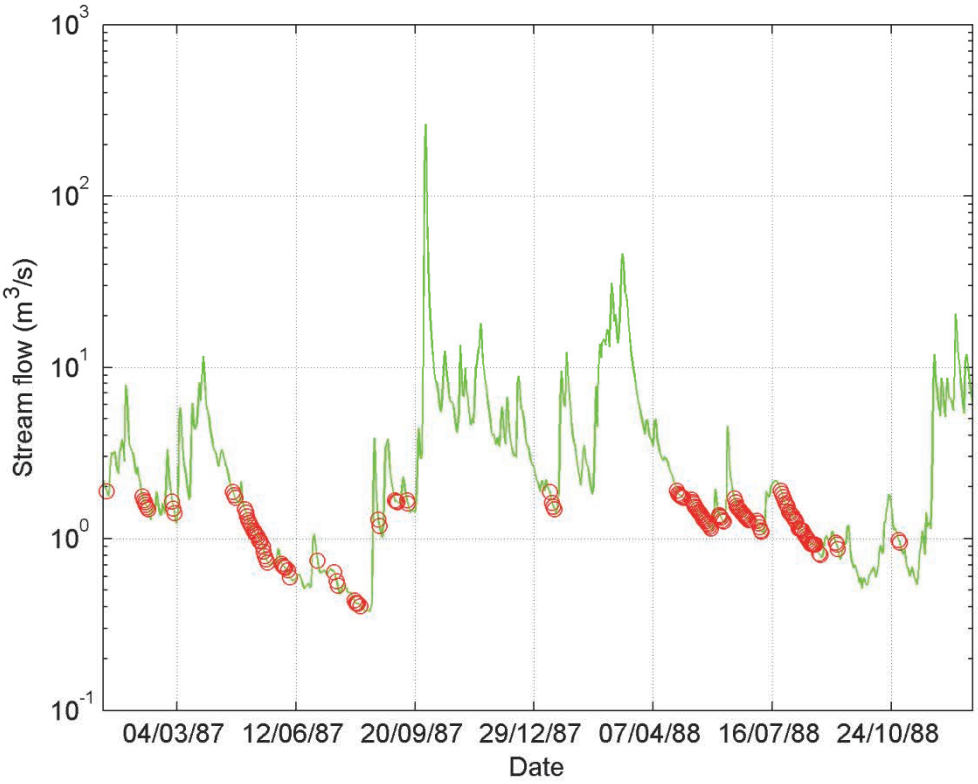

Figure 6: Daily streamflow (green) and points extracted for recession flow analysis (red circles) for station U2H013 (Y-axis is in log scale)

[3] In South Africa, 58 quality codes are used to indicate the quality of streamflow data. Quality codes 1 and 2 are used to indicate good continuous data, and good edited data, respectively. The 21 gauges have good continuous data for 60-99% of the total records and good edited data for 0-28% of the total record. On average, the selected gauges have 78% good continuous data and 16% good edited data. The combined average of good continuous data and good edited data is about 93%.

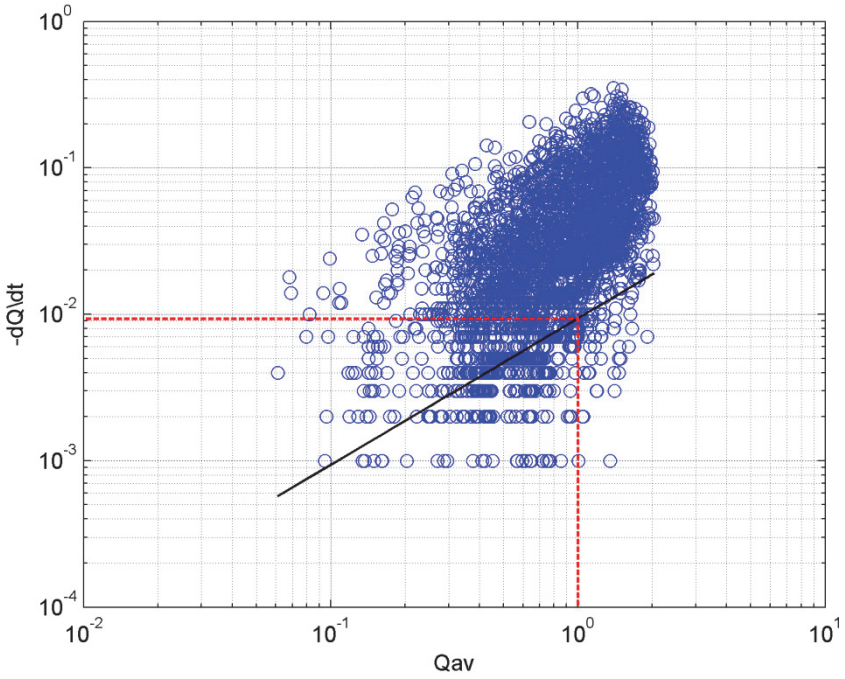

Figure 7: Data points –dQ/dt plotted against Q for the U2H013 gauging station. The lower envelope line has a unit slope, and the drainage time scale parameter is K=1/a=1/0.0094 =107 days

2.4 Baseflow separation using automated recursive digital filter method

The recursive digital filter method introduced by Nathan and McMahon (1990) was used to separate the baseflow from streamflow. The technique is arbitrary and there is no physically sound justification for its use (Nathan and McMahon, 1990). However the technique does provide an objective and automated solution for baseflow separation. Arnold et al. (1995) compared the performance of the recursive digital filter with manual separation techniques and baseflow separation with the PART[4] model over 11 watersheds in USA. Their results showed that the annual baseflow estimated with the filter method was in good agreement with the baseflow obtained using the other two methods. The filter method has the following recursive algorithm:

$$q_t = \beta q_{t-1} + \frac{1+\beta}{2} * (Q_t - Q_{t-1}) \quad (8)$$

Where q_t is the filtered surface runoff at time step t, Q_t is the original streamflow at time t and β is the filter parameter.

Baseflow b_t at time t is calculated using Equation 9:

$$b_t = Q_t - q_t \quad (9)$$

Prior to application of the algorithm, the value of β needs to be determined. According to Nathan and McMahon (1990), the value of this parameter ranges from 0.90 to 0.95, while a β value of 0.925 is recommended as optimal. On the other hand, for rivers in South Africa, Smakhtin and Watkins (Smakhtin and Watkins, 1997b) reported higher values of β, ranging from 0.985 to 0.995 and recommended 0.995 as being suitable for daily baseflow separation.

[4] A computerized method for baseflow record estimation

For the present study, we used Smakhtin and Watkins (1997) recommendation and fixed a β value of 0.995. The baseflow program implemented in MATLAB and used in this study was obtained from the BFLOW Fortran program code by Arnold et al. (1995). The BFLOW program computes baseflow by passing the filter over streamflow data three succeeding times consisting of 1-Pass, 2-Pass, and 3-Pass (i.e. forward, backward, and forward). Each pass leads to a reduction in baseflow as percent of total streamflow. Arnold and Allen (1999) reported that annual filtered baseflow with 1-Pass is consistent with baseflow estimated with manual and other automated techniques within ± 11%. More recently, Ahiablame et al. (2013) have used 1-Pass in annual baseflow separation in 22 watersheds in Indiana, USA. Therefore, in this study, we used the baseflow values generated with 1-Pass to derive a long-term baseflow index (BFI) for each quaternary catchment. BFI is the ratio of basefow to total flow calculated from a hydrograph separation procedure (either on an annual basis or for an entire observation period, determined as the ratio of total baseflow volume to total streamflow volume (Smakhtin, 2001)). BFI was initially developed in low-flow studies in the United Kingdom for characterizing the hydrological response of catchment soils and geology (Gustard et al., 1992). BFI provides a systematic way of assessing the proportion of baseflow in the total runoff of the catchment (Abebe and Foerch, 2006). Its value can be zero, if there is no baseflow, like in ephemeral streams (Smakhtin and Watkins, 1997a; Smakhtin et al., 1995) or range from 0.15 to 0.2 for an impermeable catchment with a flashy flow regime to more than 0.95 for catchments with high upstream storage capacity and a stable flow regime (WMO, 2008).

These baseflow index values were used for ecological reserve estimation following the South African procedure of ecological reserve estimation (see Section 2.5). Figure 8 shows time series of daily baseflow separation results, and Figure 9 shows time series of annual total streamflow and baseflow, aggregated from daily values for the same station.

We also tested the existence of trends and step jumps in the annual baseflow time series. Trend tests require continuous time series data for the test to be meaningful. However, our data have some data gaps despite selecting the most complete records. Hence, analysis was carried out by skipping years with missing data. Whenever data is missing, the whole year is regarded as missing and was skipped from the trend analysis. Results of the trend analysis are presented in Annex 2. Significant trends in annual baseflow were detected for seven stations, four of which had trends that were decreasing in direction and three stations show an increasing trend. CUMSUM test results also show that, of the 21 gauges, two had significant step jumps. This may indicate longer term climatic or anthropogenic impacts on the streamflow and the groundwater resources. However, no further analysis of the potential causes for the trends was done. It was assumed that the trends did not significantly change the low flow regime of the streams.

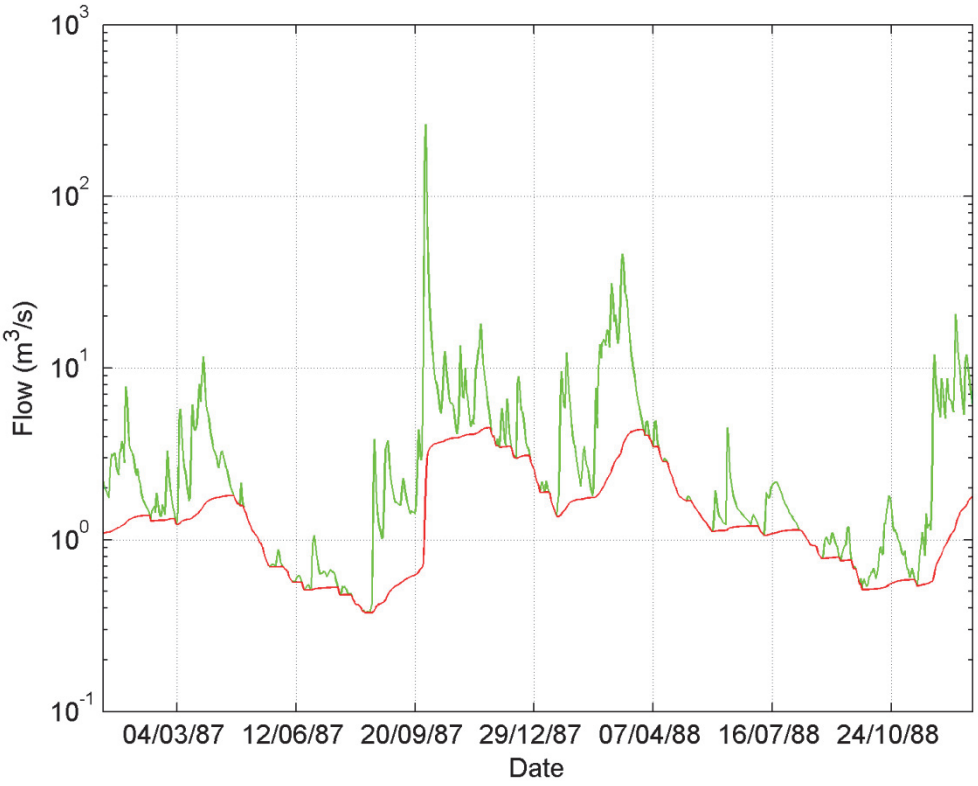

Figure 8: Daily streamflow (green) and baseflow (red) for station U2H013) (Y-axis is in log scale)

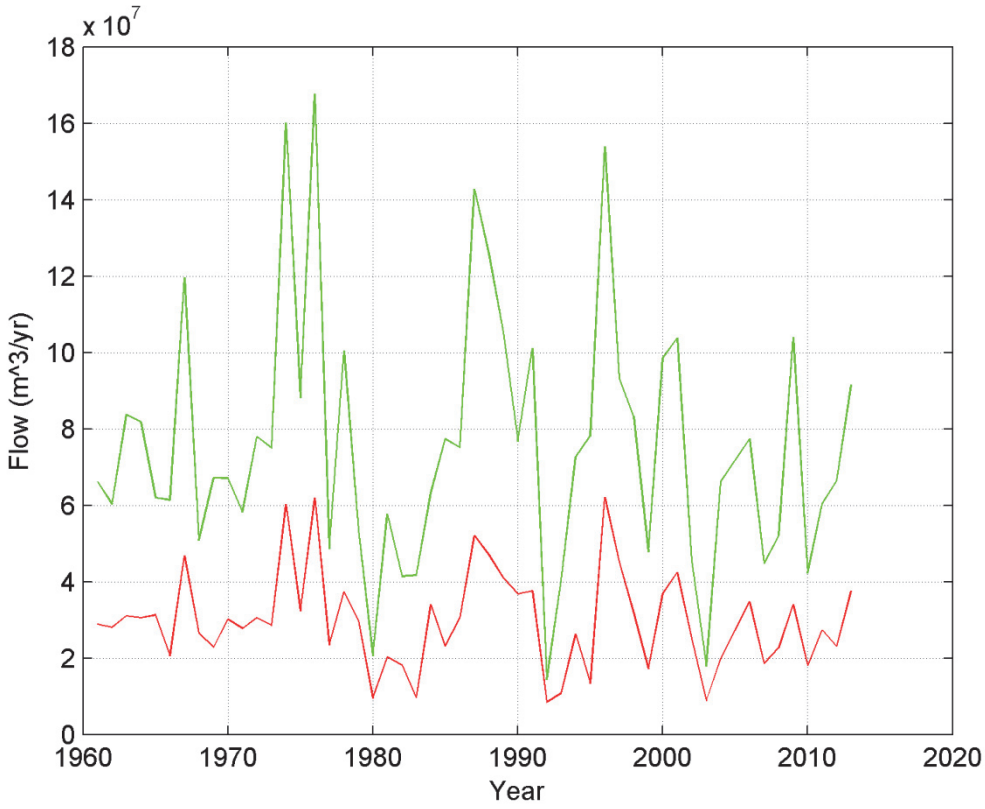

Figure 9: Annual streamflow (green) and annual baseflow (red) (station U2H013). BFI = 0.394

2.5 Estimating environmental flow requirements using the Desktop Reserve Model

The Desktop Reserve Model (DRM) was developed by the Institute of Water Research, South Africa, to provide a rapid, low confidence, initial tool for ecological reserve estimation (Hughes and Hannart, 2003). The DRM can be used to quantify the ecological reserve, which will sustain a river in a pre-determined condition. The latter is referred to as the level of ecological protection and can vary from largely natural (category A) to critically/extremely modified (category F) (Table 3).The main assumption in the DRM approach is that the ecological requirement of relatively stable (less flow varying) rivers is higher than highly variable rivers. The justification for this is that in the latter case the biota can adapt to harsh conditions and they become more tolerant to prolonged water scarcity (Hughes and Hannart, 2003). Application of the DRM for instream flow requirement estimaion is growing in different countries such as Zimbabwe (Mazvimavi et al., 2007), Tanzania (Kashaigili et al., 2007), India (Smakhtin and Anputhas, 2006), and Nepal (Smakhtin et al., 2006).

The DRM uses two measures of hydrological variability, namely the coefficient of variation (CV index) of the long-term dry and wet season flows and the long-term baseflow index (BFI) to compute the instream flow requirements. The justification of using these hydrological indices is that while CV can be used to infer long-term climatic variability, BFI is used to capture the short term variability associated with the runoff generation process. The CV index is computed as the sum of average of CVs of monthly flows of three months wet and three months dry seasons, respectively. Hughes and Hannart (2003) combined these two hydrological indices into another index (ratio of CV index to BFI), which they called the overall index of variability and named it CVB (Equation 10):

$$CVB = \frac{\text{CV index}}{\text{BFI}} \qquad (10)$$

Where

$\text{CV index} = CV\ (3\,\text{main months of } \textit{wet} \text{ seasons}) + CV\ (3\,\text{main months of } \textit{dry} \text{ seasons})$

$CV = \text{Coefficient of variation of monthly streamflows}$

$\text{BFI} = \text{Longterm baseflow index}$

The relationship between the CVB index and the maintenance[5] low instream flow requirements (MLIFR, expressed as a percentage of natural mean annual runoff (MAR)) is computed using Equation 11:

$$MLIFR = LP4 + \frac{LP1\ x\ LP2}{(CVB^{LP3})^{(1-LP1)}} \qquad (11)$$

Where LP1, LP2, LP3 and LP4 are parameters, which need to be determined for a particular level of ecological category. Hughes and Hannart (2003) analysed results of the previous comprehensive environmental flow assessment of South Africa's rivers in the context of hydrological variability of these rivers, and developed the general empirical relationship shown in Equation 11. The authors used instream flow requirements (IFRs) determined using the Building Block Methodology (BBM)[6] described in King and Louw (1998) for 97 river sites in South Africa, and estimated the LP1-LP4

[5] 'Maintenance' refers loosely to normal flow years. The actual frequency of occurrence of 'maintenance' years is expected to depend upon the flow regime variability characteristics.

[6] BBM is based on the use of expert opinion and involves several different ecological specialist (focusing on riparian vegetation, fish, invertebrates and geomorphology) for identifying the water requirements of a river

parameter values listed in Table 4 for ecological category A-D by trial and error and a visual fitting process that minimizes the overall sum of squares deviations of the IFR data points (plotted against CVB) from the fitted line (Figure 1 in Hughes and Hannart (2003)). These parameter values were used in this study without any modification. The South African Water Act of 1998 requires resource development to be carried out in environmentally sustainable manner and hence all rivers need to maintain basic ecological functioning (i.e. at least category D). That is the main reason why parameter values for ecological category E and F are not determined and included in Table 4. Equation 11 can only be used for CVB values equal to or greater than 1. According to Hughes and Hannart (2003), CVB values less than 1 are very rare for rivers in South Africa. The MLIFR determined through the DRM for a particular catchment is assumed to be constant over the years.

Table 3: Present ecological state (PES) categories used to describe the current and desired future conditions of South African rives (after Kleynhans (2000) and Nel et al. (2011))

Ecological category	**Description**
A	Unmodified, natural
B	Largely natural with few modifications. A small change in natural habitats and biota may have taken place but ecosystem functions are essentially unchanged
C	Moderately modified. A loss and change of natural habitat and biota have occurred but the basic ecosystem function are predominantly unchanged
D	Largely modified. A large loss of natural habitat, biota and basic ecosystem functions have occurred.
E	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions are extensive
F	Critically/Extremely modified. Modifications have reached a critical level and the system has been modified completely with almost complete loss of natural habitat and biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

Table 4: Parameter values of Equation 11 to estimate the annual maintenance low instream flow requirement (MLIFR) as % of MAR (Hughes and Hannart, 2003)

Parameter	**Ecological category**						
	A	A/B	B	B/C	C	C/D	D
LP1	0.900	0.905	0.910	0.915	0.920	0.925	0.930
LP2	79	61	46	37	28	24	20
LP3	6.00	5.90	5.80	5.60	5.40	5.25	5.10
LP4	8	6	4	2	0	-2	-4

To estimates environmental flows, the DRM requires a naturalized monthly flow time series (i.e. under non-disturbed conditions) (Hughes, 2003) to assess the CVB. In the present study, the monthly streamflow time series data were obtained by aggregating the daily flow data used for recession flow analysis. The wet and dry season periods for each quaternary catchment were determined using rainfall station data in close proximity to the quaternary catchments. River condition maps for present ecological categories of rivers in South Africa were obtained from National Freshwater Ecosystem Priority Areas (NFEPA) website (http://bgis.sanbi.org/NFEPA/NFEPAmap.asp) (Figure 10). The ecological categories used in Figure 10 are the same as the categories used in the DRM. Table 5 presents the present ecological categories of the rivers used in this study. Except one, all other belong to category B or C. The coefficient of variation of the wet and dry season used to calculate the overall CVB index is determined considering the rainfall in the geographic locations of the quaternary catchments (Table 6). Other parameters required by the model were obtained from Hughes and Hannart (2003) (Table 4).

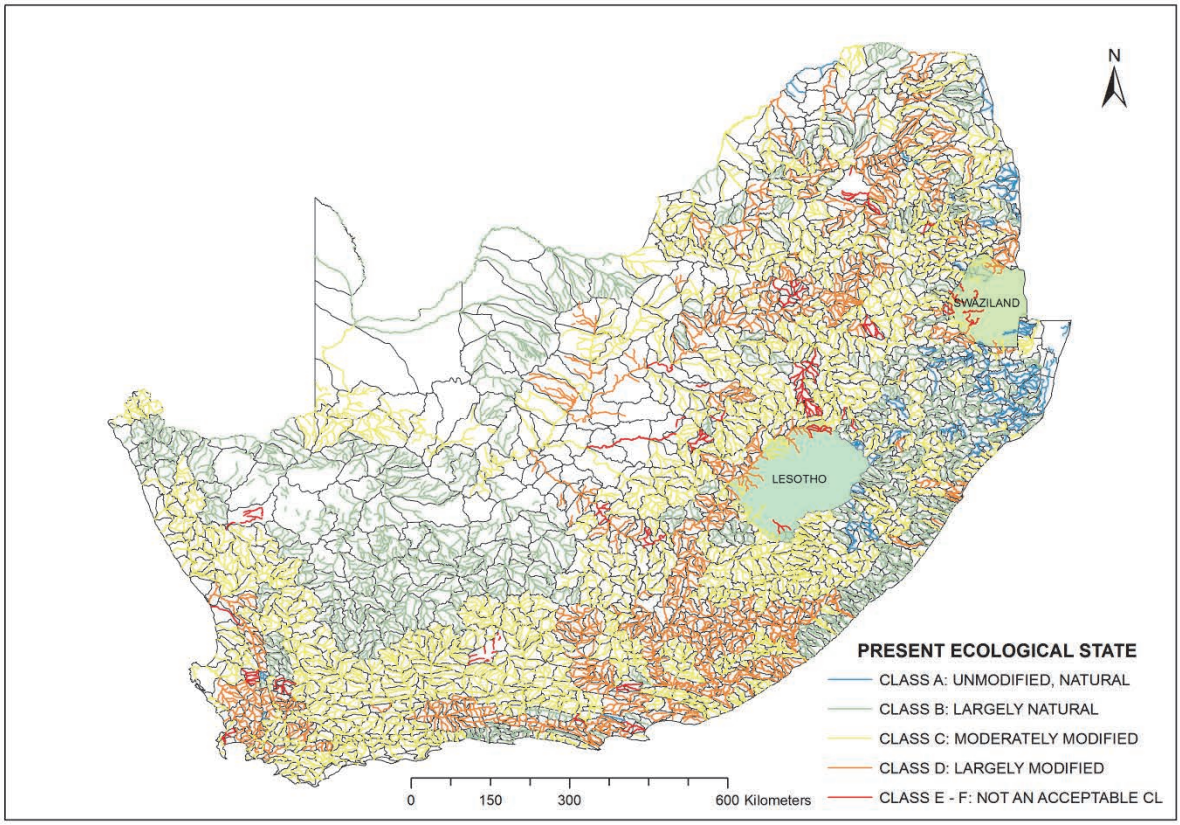

Figure 10: Present river condition in South Africa. River condition categories follow the present ecological state (PES) categories of Kleynhans (2000)

Table 5: Present ecological state (PES) of quaternary catchments

Quaternary catchment ID	**River gauge ID**	**Present Ecological state**	**Quaternary catchment ID**	**River gauge ID**	**Present Ecological state**
B81D	B8H010	C	K80C	K8H001	C
A42D	A4H008	B	K80C	K8H002	C
B73A	B7H004	C	K70B	K7H001	B
B42F	B4H005	C	K60A	K6H001	B
B11K	B1H004	C	K50A	K5H002	B
C81F	C8H005	C	K40B	K4H001	B
V60A	V6H004	A	K40C	K4H002	B
U20D	U2H006	B	K30D	K3H005	B
U20B	U2H007	C	K30A	K3H003	C
U20A	U2H013	B	K20A	K2H002	C
U70A	U7H007	C			

Table 6: Three main dry and wet months of the quaternary catchments

Quaternary catchment ID	Three main dry months	Three main wet months	Station used station and data period over which long-term mean monthly rainfall is calculated
B81D	Jun, Jul, Aug	Nov, Dec, Jan	B8E002 (1980-1994)
A42D	Jul, Aug, Sept	Nov, Dec, Jan	A4E002 (1959-1979)
B73A	Jun, Jul, Aug	Nov, Dec, Feb	B6E003 (1972-2004)
B42F	Jul, Jul, Aug	Nov, Dec, Jan	B4E003 (1972-2004)
B11K	Jun, Jul, Aug	Nov, Dec, Jan	B3E003 (1936-2013)
C81F	May, Jun, Jul	Dec, Jan, Feb	C8E009 (1994-2013)
V60A	May, Jun, Jul	Dec, Jan, Feb	V1E005 (1969-2013)
U20A and U20B	May, Jun, Jul	Dec, Jan, Feb	U2E003 (1965-2013)
U70A	Jun, Jul, Aug	Dec, Jan, Feb	U6E002 (1932-2013)
K60A, K20A K50A, K30 D, K80C, K30A and K70B	May, Jun, Jul	Oct, Nov, Dec	K2E001 (1989-2013) and K3E003 (1978-2013)

3. Results

3.1 Drainage time scale

The drainage time scales of the quaternary catchments are presented in Table 7. The computed drainage time scale in the study area ranges from 28 to 168 days. Brutsaert (2008) reported that the drainage time scale for larger basins is relatively invariant and is in the order of 1.5 months with an uncertainty of two weeks and adopted a constant value as a working assumption in a subsequent study (e.g., Brutsaert (2010)). According to Brutsaert and Sugita (2008), over large catchments, many of the controlling effects (i.e. drainable porosity, hydraulic transmissivity of the contributing unconfined aquifer, and drainage density of the river network) will average out or compensate one another and the value of the drainage time scale within similar climatic conditions are expected to be of similar order of magnitude. Erosion and weathering processes with time in larger river basins will cause the physical properties and structure of the river network to evolve to an equilibrium state (Brutsaert, 2008). However, for smaller catchments, the variability tends to increase (Skøien et al., 2003). Tague and Grant (2009) analysed four catchments ranging in size from 2.6 to 465 km^2 in Oregon and California and reported drainage time scales that cover a wide range, namely between 26 and 100 days. Drainage time scale values from past studies are listed in Table 8. The drainage time scales obtained in this study are within the range of Tague and Grant (2009) reported values, although some values are higher than 45 ± 15 days suggested by Brutsaert (2008). Lyon et al.(2014) reported higher values of K, ranging from 61-435 days than suggested by Brutsaert (2008). Chapman and Peck (1997) found that K varies with season (Table 8). Figure 11 shows the relationships between drainage time scale and catchment area from previous studies presented in Table 8. As catchment scale decreases, the variability in drainage time scale tends to increase. Clearly, more research is needed to further validate the approach and determine factors physically explaining the drainage time scale.

Table 7: Drainage time scale (K) of quaternary catchments

Quaternary catchment ID	River gauge ID	Upstream catchment area (km^2)	Drainage time scale, K (day)	Quaternary catchment ID	River gauge ID	Upstream catchment area (km^2)	Drainage time scale, K (day)
B81D	B8H010	565	53.1	K80C	K8H001	38	27.5
A42D	A4H008	597	84.0	K80C	K8H002	51	45.5
B73A	B7H004	163	85.3	K70B	K7H001	83	62.8
B42F	B4H005	232	119.0	K60A	K6H001	267	39.5
B11K	B1H004	464	168.0	K50A	K5H002	194	67.8
C81F	C8H005	902	64.6	K40B	K4H001	162	84.5
V60A	V6H004	851	65.0	K40C	K4H002	33	33.5
U20D	U2H006	318	82.7	K30D	K3H005	113	54.5
U20B	U2H007	466	111.0	K30A	K3H003	211	33.3
U20A	U2H013	391	107.0	K20A	K2H002	189	34.0
U70A	U7H007	151	120.0				

Table 8: Drainage time scale values from the literature

Location	Drainage area (km^2)	Drainage time scale, K (days)	References
Lookout Creek, Oregon	64	36	Tague and Grant (2009)
McKenzie River at Clear Lake, Oregon	239	100	
Sagehen Creek, California	2.6	37	
Upper Merced River at Happy Isles, California	465	26	
Kherlen River Baganuur gauging station, Mongolia	7350	41	Brutsaert and Sugita (2008)
Kherlen River Undurkhaan gauging station, Mongolia	39400	43	
Kherlen River Choibalsan gauging station, Mongolia	71500	48	
Illinois River at Valley City, III	69227	37	Brutsaert (2008)
Rock River near, Joslin II	24721	46	
Upper Lena basin, station location Solyanka, Eastern Siberia	770000	52	Brutsaert and Hiyama (2012)

Location	Drainage area (km^2)	Drainage time scale, K (days)	References
Olyokma basin, station location Kudu-kel, Eastern Siberia	115000	29	Drainage time scale values were calculated as average of decadal drainage time scale.
Aldan-1 basin, station location Ochotski Perevoz, Eastern Siberia	514000	36	
Aldan-2 basin, station location Verkhoyanski Perevoz, Eastern Siberia	696000	46	
Chattahoochee River at Helen, Northern Georgia	116	43 (65)	Chapman and Peck (1997), Table 5 Drainage time scale values were calculated separately for summer and winter seasons. Values in bracket are for winter seasons. Average values were used in Figure 17.
Chattahoochee River near Leaf, Northern Georgia	389	43 (52)	
Chattahoochee River near Gainesville, Northern Georgia	1449	52 (65)	
Chattahoochee River near Buford, Northern Georgia	2745	56 (65)	
Chattahoochee River at Atlanta, Northern Georgia	3756	52 (65)	
Chattahoochee River near Whitesburg, Northern Georgia	6268	43 (57)	
Catchment ID L1	34230	154	Lyon et al.(2014) case study area Kilombero valley, Tanzania Driange time scale values were determiend using all avialble streamflow data and considering each month separtely. Here, driange time scale values obatined using available data are presented.
Catchment ID L2	18048	286	
Catchment ID L3	8577	400	
Catchment ID L4,	2531	189	
Catchment ID S1,	580	97	
Catchment ID S2,	582	435	
Catchment ID S3	337	61	
Catchment ID S4	336	137	
Catchment ID S5	175	70	

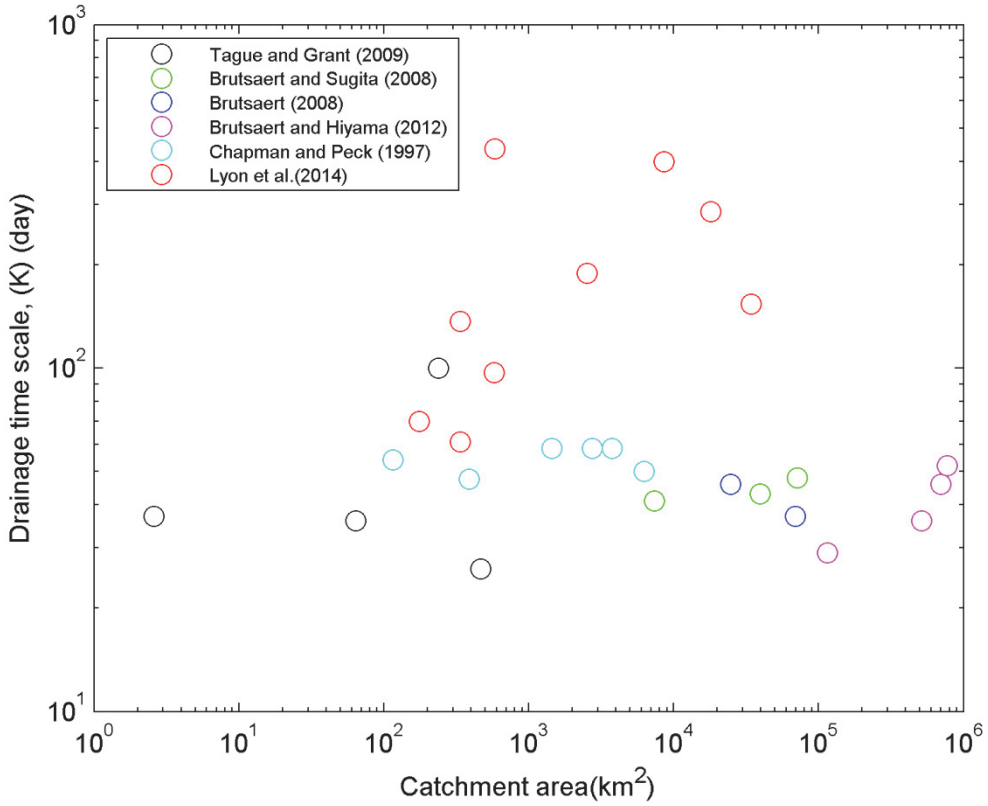

Figure 11: Relationship between catchment area and drainage time scale (from previous studies)

3.2 Baseflow index

The baseflow index (BFI) across the quaternary catchments ranges from 0.14 to 0.54 (Table 9). Gauges located at the southern coast region have relatively low BFI values. The BFI was found to be strongly correlated with drainage time scale (correlation coefficient= 0.92). The linear regression between BFI and drainage time scale (Figure 12) shows that about 86% of the variance in drainage time scale can be explained by the BFI (R^2=0.86). This is physically plausible. As the drainage time scale increases (drainable porosity increases and transmissivity and drainage density decreases, Equation 5), drainage is attenuated and prolonged, which is consistent with a larger fraction of baseflow.

Table 9: Baseflow index and drainage constant of the quaternary catchments

Quaternary catchment ID	River gauge ID	Upstream catchment area (km^2)	BFI (β=0.995)	K value (day)
B81D	B8H010	565	0.339	53.1
A42D	A4H008	597	0.428	84.0
B73A	B7H004	163	0.373	85.3
B42F	B4H005	232	0.489	119.0
B11K	B1H004	464	0.541	168.0
C81F	C8H005	902	0.275	64.6
V60A	V6H004	851	0.239	65.0
U20D	U2H006	318	0.388	82.7
U20B	U2H007	466	0.420	111.0
U20A	U2H013	391	0.394	107.0
U70A	U7H007	151	0.446	120.0
K80C	K8H001	38	0.196	27.5
K80C	K8H002	51	0.255	45.5
K70B	K7H001	83	0.289	62.8
K60A	K6H001	267	0.239	39.5
K50A	K5H002	194	0.340	67.8
K40B	K4H001	162	0.308	84.5
K40C	K4H002	33	0.186	33.5
K30D	K3H005	113	0.286	54.5
K30A	K3H003	211	0.152	33.3
K20A	K2H002	189	0.144	34.0

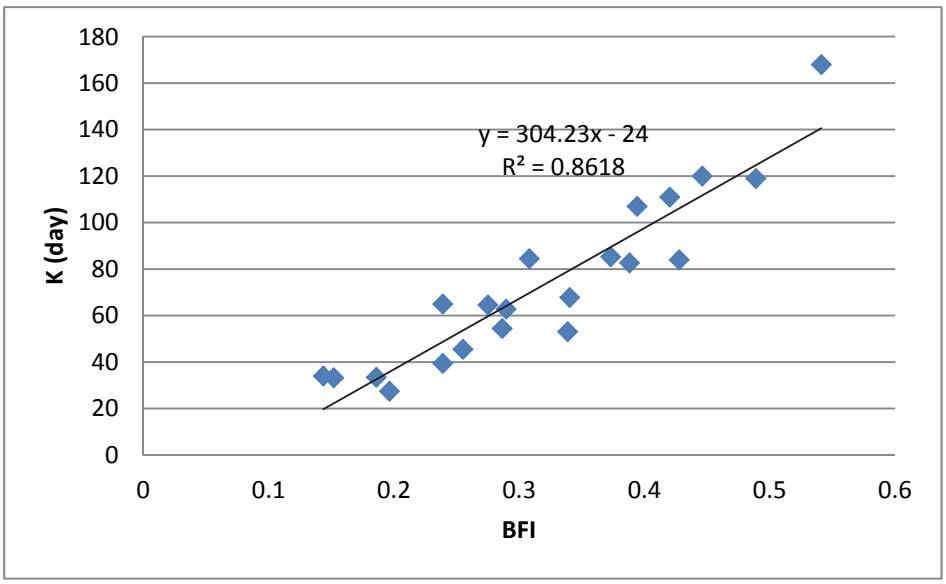

Figure 12: Relationships between baseflow index (BFI) and drainage time scale (K)

3.3 Estimation of environmental flow requirements

Results of the study presented in Table 10 show that to maintain the rivers in present ecological categories, approximately 7 to 25% of the mean annual river flow in different catchments needs to be allocated to freshwater dependent ecosystems. The higher the ecological class, the more water needs to be allocated for ecosystem maintenance and vice versa. For instance, the MLIFR is higher for quaternary catchment V60A, for which the river condition is required to be maintained at target ''A''.

Table 10: Maintenance low instream flow requirements (MLIFR) as a percentage of mean annual runoff (MAR) for the quaternary catchments, using present PES for MLIFR determination

Quaternary catchment ID	Gauge ID	PES	MAR (MCM/yr)	BFI	Mean CV-wet season	Mean CV-dry season	CVB-index	MLIFR (% MAR)
B81D	B8H010	C	68.2	0.339	1.21	1.31	7.46	10.8
A42D	A4H008	B	38.0	0.428	1.09	0.97	4.82	22.4
B73A	B7H004	C	27.0	0.373	1.08	0.74	4.89	13.0
B42F	B4H005	C	22.9	0.489	0.74	0.59	2.74	16.7
B11K	B1H004	C	31.4	0.541	0.85	0.67	2.81	16.5
C81F	C8H005	C	105.0	0.275	1.00	0.73	6.28	11.6
V60A	V6H004	A	94.2	0.239	0.85	1.46	9.62	26.3
U20D	U2H006	B	88.3	0.388	0.81	0.76	4.06	24.1
U20B	U2H007	C	61.4	0.420	0.88	0.68	3.71	14.6
U20A	U2H013	B	75.5	0.394	0.76	0.71	3.73	25.1
U70A	U7H007	C	11.1	0.446	1.07	0.70	3.97	14.2
K80C	K8H001	C	17.4	0.196	0.81	1.11	9.76	9.63
K80C	K8H002	C	16.3	0.255	0.97	1.23	8.63	10.2
K70B	K7H001	B	26.5	0.289	0.92	1.20	7.32	18.8
K60A	K6H001	B	10.7	0.239	1.89	2.20	17.10	13.5
K50A	K5H002	B	24.1	0.340	1.11	1.28	7.01	19.1
K40B	K4H001	B	25.0	0.308	0.86	1.49	7.63	18.5
K40C	K4H002	B	9.4	0.186	1.06	1.39	13.2	14.9
K30D	K3H005	B	12.3	0.286	1.42	1.52	10.3	16.4
K30A	K3H003	C	27.6	0.152	1.55	1.94	23.0	6.65
K20A	K2H002	C	16.8	0.144	1.48	2.18	25.5	6.4

3.4 Determining upper limit of groundwater allocation and groundwater reserve

To determine the upper limit for groundwater allocation, baseflow in excess of present PES-MLIFR (here onwards used to specify the MLIFR corresponding to the PES for the catchment in question, Table 10) is calculated by subtracting present PES-MLIFR from annual baseflow values. These baseflow surplus values are then converted to annual available groundwater storage volumes by multiplying with the drainage time scale (Equation 6). The available storage of each quaternary catchment is then divided by their respective drainage area to determine the annual average available thickness of a layer of water above zero flow level spread over the catchment area. Depth

duration curves analogue to flow duration curves (i.e. cumulative frequency curves) are generated in order to express the percentage of time a specified groundwater thickness is equal to or exceeded during a given period. Kannan and Jeong (2011) discussed five parts of flow duration curves. These include: (i) parts representing high flows (0-10%), (ii) moist conditions (10-40%), (iii) mid-range flows (40-60%), low flows (60-90%), and dry conditions (90-100%). The mid points of the moist, mid-range and low flows parts correspond to the quartiles (25th, 50th, and 75th, respectively). The high and dry parts centred at the 5th and 95th percentiles, respectively. Assuming that the duration curves for groundwater storage in the catchment behave similarly, we used the 75th percentile to determine the upper limit of groundwater abstraction. Figure 13 shows the annual groundwater storage depth in excess of present PES-MLIFR. As it can be seen, the available groundwater storage is highly variable across the years for some of the catchments, while for others it is rather constant. In some years, the available groundwater storage is below zero, which indicates that the available groundwater is not even sufficient for satisfying the MLIFR, if the current PES is to be maintained. Figure 14 shows the box plot of the available groundwater storage depth for the same data set used in Figure 13. What is obvious from this figure is that catchments located in southern coast have relatively low available groundwater storage depth for allocation, and as one moves to the north the available storage depth increases.

The same data set used in Figure 13 and 14 is used to plot the depth duration curves shown in Figure 15. The lower portion of these curves is more important for analysis as it represents dry conditions. Of the twenty-one catchments, only one (K80C, two gauges, K8H001 and K8H002) has allocatable groundwater storage above zero all the years. On the other hand, in catchments V60A and K60A, the allocatable groundwater storage is above zero only 38 and 51% of the time, respectively (Table 11). Table 11 also gives the annual groundwater storage thickness and volume that is available 75% of the time as a measure of the upper limit to sustainable groundwater exploitation, ensuring the satisfaction of present PES-MLIFR 75% of the time. Three out of the twenty-one catchments, namely V60A, K60A, and K40C have negative storage at 75 percentile, which indicates that the annual baseflow is not sufficient to maintain present PES-MLIFR 75% of the time.

Table 12 presents the groundwater reserve equivalent to the present PES-MLIFR, given both as a storage volume and a storage depth. The groundwater reserve storage across the selected quaternary catchments varies from 0.1 to 5.6 MCM. Catchments located in the south coast have relatively low groundwater reserve compared to catchments located in the north.

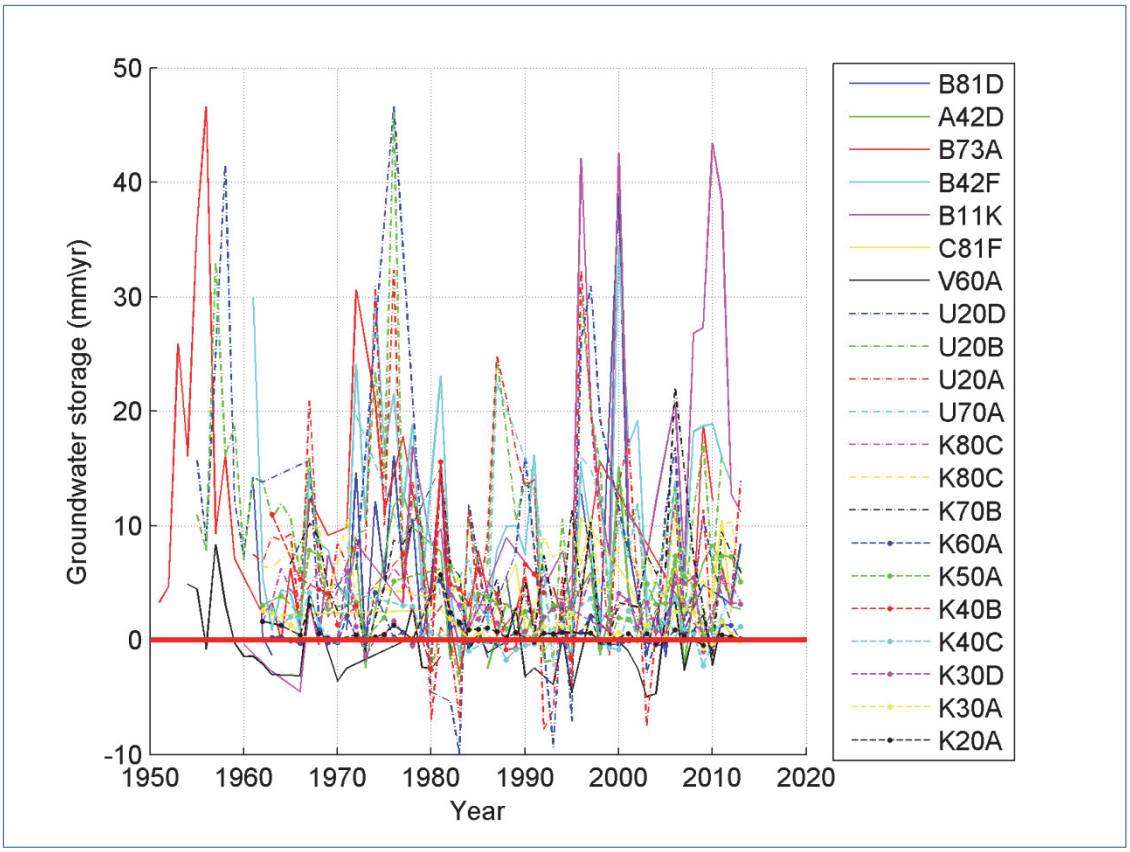

Figure 13: Time series of annual groundwater storage depth in excess of present PES-MLIFR for the quaternary catchments

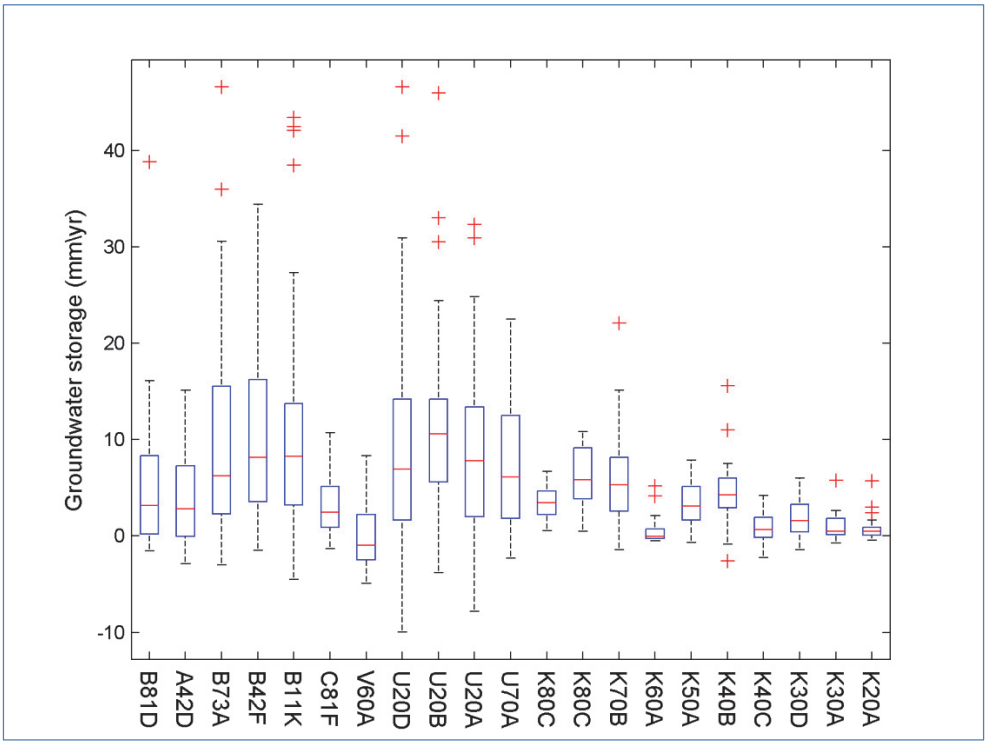

Figure 14: Box plot of annual groundwater storage depth in excess of present PES-MLIFR for the quaternary catchments

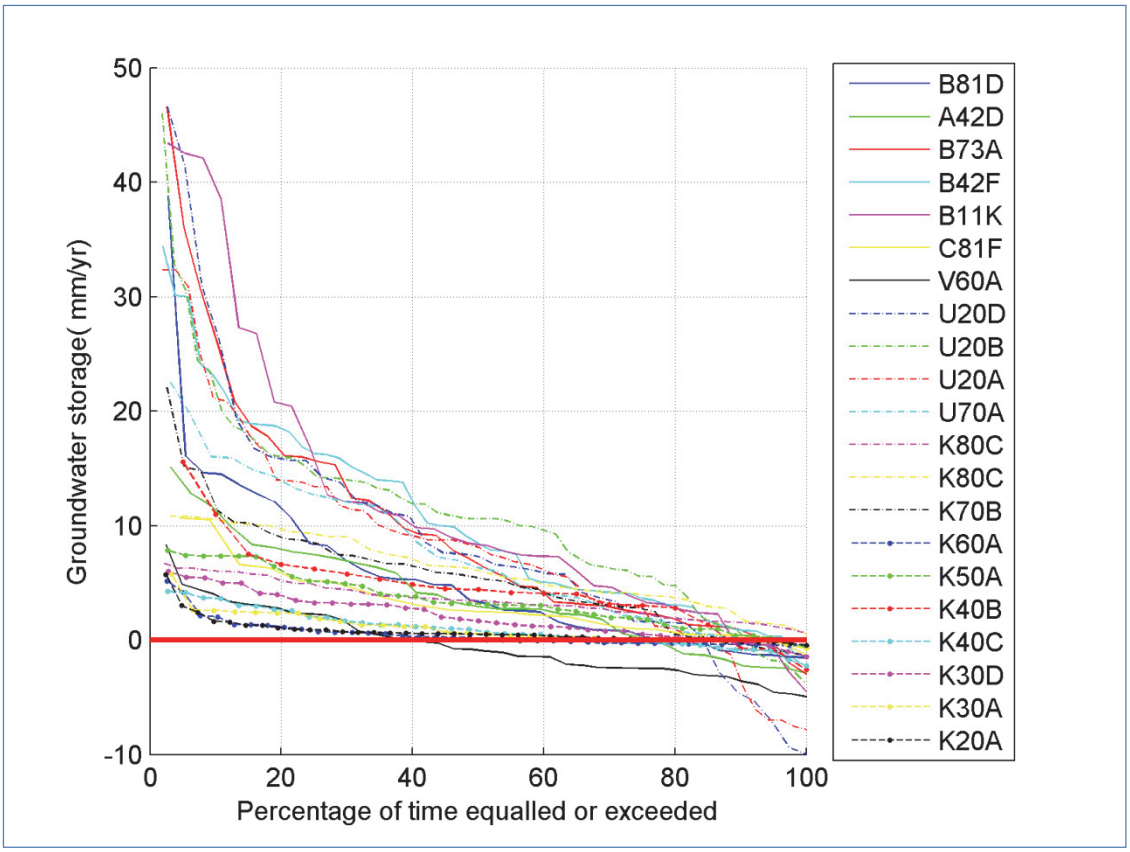

Figure 15: Groundwater excess storage depth duration curves for the quaternary catchments

Table 11: Percentage of time annual allocatable groundwater storage is equal to or greater than zero, and upper limit for groundwater allocation, using the 75 % percentile

Quaternary catchment ID	River gauge ID	Area (km^2)	% of time groundwater storage exceeds or equal to Zero	Groundwater storage thickness available 75% of the time (mm/yr)	Groundwater storage volume available 75% of the time (MCM/yr)
B81D	B8H010	565	82	0.36	0.20
A42D	A4H008	597	76	0.14	0.08
B73A	B7H004	163	94	2.36	0.38
B42F	B4H005	466	97	3.64	1.70
B11K	B1H004	464	89	3.41	1.58
C81F	C8H005	902	96	0.96	0.87
V60A	V6H004	851	38	-2.47	-2.10
U20D	U2H006	318	84	1.63	0.52
U20B	U2H007	232	91	5.58	1.29
U20A	U2H013	391	82	2.81	1.10
U70A	U7H007	151	94	2.00	0.30
K80C	K8H001	113	100	2.31	0.26
K80C	K8H002	51	100	3.95	0.20
K70B	K7H001	189	89	2.73	0.52
K60A	K6H001	38	51	-0.27	-0.01
K50A	K5H002	194	96	1.82	0.35
K40B	K4H001	162	88	3.02	0.49
K40C	K4H002	33	67	-0.12	0.00
K30D	K3H005	267	87	0.52	0.14
K30A	K3H003	211	86	0.13	0.03
K20A	K2H002	83	85	0.09	0.01

Table 12: Ecological groundwater reserve storage, equivalent to present PES-MLIFR

Catchment ID	River gauge ID	Area (km^2)	MAR (MCM/yr)	MLIFR (% of MAR)	K (day)	Groundwater reserve storage (MCM/yr)	Groundwater reserve storage thickness (mm/yr),
B81D	B8H010	565	68.2	10.8	53.1	1.07	1.90
A42D	A4H008	597	38.0	22.4	84.0	1.96	3.28
B73A	B7H004	163	27.0	13.0	85.3	0.82	5.03
B42F	B4H005	466	22.9	16.7	119.0	1.25	2.68
B11K	B1H004	464	31.4	16.5	168	2.38	5.14
C81F	C8H005	902	105.0	11.6	64.6	2.16	2.39
V60A	V6H004	851	94.2	26.3	65.0	4.41	5.18
U20D	U2H006	318	88.3	24.1	82.7	4.82	15.16
U20B	U2H007	232	61.4	14.6	111.0	2.73	11.75
U20A	U2H013	391	75.5	25.1	107.0	5.56	14.21
U70A	U7H007	151	11.1	14.2	120.0	0.52	3.43
K80C	K8H001	113	17.4	9.6	27.5	0.13	1.11
K80C	K8H002	51	16.3	10.2	45.5	0.21	4.06
K70B	K7H001	189	26.5	18.8	62.8	0.86	4.54
K60A	K6H001	38	10.7	13.5	39.5	0.16	4.11
K50A	K5H002	194	24.1	19.1	67.8	0.86	4.41
K40B	K4H001	162	25.0	18.5	84.5	1.07	6.61
K40C	K4H002	33	9.4	14.9	33.5	0.13	3.90
K30D	K3H005	267	12.3	16.4	54.5	0.30	1.13
K30A	K3H003	211	27.6	6.7	33.3	0.17	0.80
K20A	K2H002	83	16.8	6.4	34.0	0.10	1.21

4. Discussion

The groundwater component of the reserve comprises of two parts: the basic human needs (BHN) reserve that is required to satisfy the basic human needs and the groundwater component of the ecological reserve; a portion derived from groundwater that is required to protect the aquatic ecosystems. These two reserve components are given highest priority by the NWA in allocating groundwater from a particular aquifer. Any further groundwater allocation to other beneficial and sustainable uses can only be done after fulfilling these two needs. This study estimated the groundwater component of the ecological reserve in twenty-one quaternary catchments in South Africa as well as the groundwater resources available for human needs, including for BHN. Hence, and because the catchments were relatively undeveloped, the BHN part of the reserve was not accounted for. Therefore, once the total BHN for a particular catchment is known, provision to other beneficial uses can be made after subtracting the total BHN volume from the available allocatable groundwater storage.

The approach demonstrated in this study to estimate the allocatable groundwater storage was applied to rivers, which have perennial flow and a relatively non-insignificant level of baseflow (BFI>0.25). It remains to be tested if the method is applicable for catchments with lower relative baseflow contribution. In addition, the rivers were not appreciably affected by human activities (i.e. regulations, diversion, or other man-made alteration). This approach ensured minimal human impacts on low flow regimes. It was assumed that temporal trends or sudden changes in baseflow regime were insignificant. However, some trends were detected and further analysis is required to assess possible implications for the results.

The drainage time scale was found to be strongly correlated with the baseflow index, BFI (R^2= 0.86), which indicates that the drainage time scale can be estimated indirectly from the baseflow data, omitting one step in the computation process. This is very useful, as the determination of the drainage time scale is time consuming relative to the baseflow separation.

We found that the results of the baseflow estimation are very sensitive to the digital filter parameter β (data not shown). For a small increase in β, from 0.925 to 0.990, the average BFI value for the twenty-one catchments decreases from 0.58 to 0.32 (i.e. about 55% reduction in BFI). This, in turn implies significant reduction in allocatable groundwater. It has already been made clear that baseflow separation techniques based solely on the analysis of streamflow hydrographs are inherently arbitrary in nature, and without field observation data the true base flow contribution cannot be confidently determined (Nathan and McMahon, 1990). Hence, we cannot determine with confidence the appropriateness of the filter parameter used. However, we used a filter parameter value (β = 0.995) used and tested in previous studies in South Africa (Smakhtin and Watkins, 1997b). We obtain relatively low BFI values, from 0.15 to 0.54, which are generally lower than the values mapped in Hughes et al. (2007). Our approach for determining allocatable groundwater hence is conservative and applying higher BFI values (lower β values) would result in higher groundwater availability.

Furthermore, the results depend strongly on the PES applied to determine the MLIFR. In the present study, the present PES-MLIFR was applied to illustrate the methodology.

The source of baseflow is usually the unconfined aquifer where the river channel is in hydraulic connection with the aquifer. Limiting groundwater abstraction from areas in close proximity to the river improves the baseflow conditions. That means that allocating groundwater abstraction permits further away from the river may not strongly influence the baseflow (Rushton, 2002).

It was not attempted to estimate monthly MLIFR by using the seasonal distribution functionality of the DRM. However, the same principle can be applied for estimating monthly groundwater storage available for abstraction. At the same time, by using established assurance rules available in DRM for South African rives that specify the expected frequency of MLIFR, monthly groundwater storage estimation for different levels of assurances can be made. However, since groundwater storage is replenished and released slowly and the amount released may be relatively small compared to the total groundwater storage volume, implying that the aquifer can play a certain buffering role, it was assumed that doing the calculations on an annual basis was adequate.

Finally, the assessment made no separate assessment of the aquifer classification *per se*, which is a component of the GRDMs. The ecological requirements were solely based on the classification of the recipient streams. However, some concerns on the aquifer itself may be relevant, to protect it from degradation, e.g. though exaggerated groundwater level declines, which for example could adversely impact important phreatic vegetation. As stated by Parsons and Wentzel (2007), GWL will often be an accompanying criterion in determining reserves. Similarly, no water quality aspects were taken into consideration in the reserve determination. This will also have to be included for any meaningful and comprehensive GRDM assessment.

5. Conclusions

Determining groundwater allocation based on good scientific understanding and adhering to sound sustainability and social equity principles are critical. The study proposed an alternative methodology for determining the groundwater reserve. Rather than using recharge as the upper limit for groundwater abstraction (Equation 1) as proposed by Parsons and Wentzel (2007), baseflow in unregulated streams was assumed to be a good indicator of groundwater availability in the catchment. Using baseflow separation and recession flow analysis, and established knowledge and practise for determining ecological flow requirements of rivers in South Africa, through the Desktop Reserve Model, the surplus baseflow in excess of the ecological flow requirements were assumed to be representative of available groundwater in upper parts of the catchment in unconfined aquifers, represented as linear reservoirs. This available groundwater is allocatable for all human uses, including basic human needs.

The approach was demonstrated and showcased for twenty-one perennial and relatively undeveloped quaternary catchments with good and long streamflow records and using the present ecological status of these streams as target for instream flow requirements and subsequently for estimating available groundwater.

Results show that groundwater availability varies spatially across the investigated sites and despite groundwater being a buffer, availability also shows variability across the years. Assuming that an exceedance level of 75 % of the years is relevant for the assessment of the groundwater availability on a long-term basis, it was found that the upper limit for groundwater allocation over the

catchments varies between -2.1 and 1.58 MCM/yr. The ecological groundwater reserve storage, equivalent to present PES-MLIFR, varies from 0.1 to 5.6 MCM, which need to be left in the aquifers to ascertain sufficient river flow. Three out of the twenty-one catchments have negative storage at 75% exceedance, indicating that the annual baseflow in these catchments is not enough to meet present PES-MLIFR, let alone further groundwater development. The basic human need reserve was not set aside during the available groundwater storage calculation. Hence the available groundwater calculated in this study needs to be allocated first to fulfil basic human needs.

In general, the approach proved as a very useful tool to assist in assessing ecological needs for groundwater as part of determining the Reserve and for determining available groundwater for further satisfying basic human needs and other development needs. Its novelty lies in the combination of various existing methodologies for assessing baseflows, recession flows and instream flow requirements to extract valuable information on groundwater behaviour, like its drainage characteristics to streams, as well as quantitative estimation of available groundwater volumes and it spatial and temporal variability within South Africa.

Further work is required to refine and further test the method, resolving some of the uncertainties relate to the baseflow separation methods, as well as the application to stream with lower baseflow indices (BFI<0.25). However, this method will not be applicable to ephemeral streams where baseflows are insignificant.

Finally, the method will have to be tested in actual Reserve determinations, and contrasted with previous groundwater reserve methods, while ensuring that linking to other components of the groundwater resource directed measures are taken into account.

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Annex

Annex1: Potential streamflow gauging stations (57 in total) with corresponding coordinates, period of record, drainage area and selection criteria used (rows in green indicate 21 stations selected as good candidates)

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)	Province	Criteria
B73A	B7H004	Mohlolobe	-24.55622	31.03225	1950-11-01 2014-02-11	136	LP	
B73A	B7H022	Left Upstream Canal @ Fleur De Lys	-24.54081	31.03813	1961-09-07-2012-01-17	unknown	LP	Missing information (area)
B73A	B7H024	Right Canal From Dam To River @ Fleur De Lys	-24.52358	31.07094	1961-09-01-2012-01-17	unknown	LP	Missing information (area)
B60D	B6H001	Blyde	-24.68025	30.80213	1909-11-11 2014-03-13	518	MP	huge data gap (1926/10/01-1958/08/25)
B71H	B7H009	Olifants River @ Finale	-24.33116	30.74163	1960-08-30 2014-02-17	42472	LP	not a quaternary catchment
U20A	U2H013	Mgeni River @ Petrus Stroom	-29.51261	30.09442	1960-08-10 2014-02-25	299	KZN	
U20B	U2H007	Lions River@(Mpofana River) @ Weltevreden	-29.44258	30.14853	1954-07-16 2013-09-23	358	KZN	
U20B	U2H061	Mpofana River	-29.39162	30.06297	2013-02-26 2014-03-10	unknown	KZN	Missing information (area)
U20C	U2H045	Nguku River @ Grootvlei	-29.5459	30.17142	1988-08-26 1992-06-12	30	KZN	Short record length
U20C	U2H044	Umthinzima River @ Rietvallei	-29.55257	30.18836	1988-08-16 1992-05-15	19	KZN	Short record length
U20c	U2H048	Mgeni River @ Midmar	-29.493	30.203	1968-03-11 2014-02-07	928	KZN	Dam at the upstream side
U40A	U4H002	Mvoti River @ Mistle	-29.16192	30.630	1949-08-12 2014-03-12	316	KZN	Time series b/n 1949-1970s is smaller
U30C	U3H001	Tongati River @ Riet Kuil	-29.53368	31.08922	1966-10-07 2014-02-13	236	KZN	huge data gap (1992/11/30-2006/04/04)
U30A	U3H002	Mdloti River @ Roodekrans	-29.60312	31.01644	1950-08-23 1977-01-20	356	KZN	Short record length
U30A	U3H005	Mdloti River @ Cotton Lands	-29.596	31.047	1975-11-01 2014-02-13	377	KZN	

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)	Province	Criteria
U20D	U2H006	Karkloof River @ Shafton	-29.38175	30.27775	1954-01-04 2014-02-25	339	KZN	
U20B	U2H061	Mpofana River	-29.39162	30.06297	2013-02-26 2014-03-10	unknown	KZN	Missing information (area) plus short record length
U60A	U6H002	Mlazi River @ Nooitgedacht	-29.749	30.317	1981-07-13 2014-02-28	105	KZN	Short record length
U70A	U7H001	Zwateni River @ Highlands	-29.84733	30.23531	1949-07-09 2013-11-01	16	KZN	data gaps, and time series like regulated flow
U70A	U7H007	Lovu River @ Beaulieu Estate	-29.86244	30.24417	1964-10-13 2014-02-28	114	KZN	
K80C	K8H001	Kruis River @ Farm 508	-33.98194	24.02097	1961-06-20 2014-05-15	26	EC	
K80C	K8H002	Elands River @ Kwaai Brand For. Re	-33.98136	24.05014	1961-07-11 2014-05-15	35	EC	
K80D	K8H006	Groot River @ Rooiwal	-34.03197	24.19553	1998-09-29 2014-05-15	unknown	EC	Missing information (area) plus short record length
K80E	K8H005	Groot	-34.09664	24.43911	1995-06-20 2014-03-11	unknown	EC	Missing information (area) plus short record length
K90B	K9H001	Krom River @ Kromme Riviers Poort	-34.00586	24.49914	1948-09-01 2014-05-14	369	EC	data gaps (1949/04/02-1955/01/31)
K60G	K6H003	River Outlet @ Roodefontein	-34.06833	23.33611	1996-01-01 2014-02-25	unknown	WC	Missing information (area) plus short record length
K60A	K6H001	Keurbooms River @ M'Kama	-33.80361	23.13528	1961-08-19 2014-02-18	165	WC	
K50B	K5H001	Gouna River @ Gouna Commonage Con-	-33.99121	23.04201	1959-11-16 1984-10-22	91	WC	Short record length
K50A	K5H002	Knysna River @ Milwood Forest Res.	-33.89111	23.02944	1961-08-02 2014-02-25	133	WC	

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)	Province	Criteria
K50B	K5H003	Knysna River @ Charlesford	-33.99833	23.00306	2003-05-14 2014-02-25	unknown	WC	Missing information (area) plus short record length
K40B	K4H001	Hoekraal River @ Eastbrook	-33.97982	22.7995	1959-11-19 1993-05-17	111	WC	Short record length
K30D	K3H005	Touws River @ Farm 162	-33.94528	22.61444	1969-04-15 2014-03-05	78	WC	
K30D	K3H011	Duiwe River @ Klein Krantz	-33.98167	22.65139	1996-08-12 2014-03-05	33	WC	Short record length
K30A	K3H003	Maalgate River @ Knoetze Kama	-34.00667	22.35028	1961-04-06 2014-03-07	145	WC	
J35B	J3H017	Kandelaars River @ Paardendrift	-33.67917	22.14	1969-04-07 2014-02-11	348	WC	Time series with zero flows (not perennial)
J35B	J3H005	Klip River @ Klippe Drift	-33.77928	22.3231	1926-03-01 1947-09-30	95	WC	Short record length
J35B	J3H010	Klip River @ Welbedag	-33.76955	22.31505	1963-06-15 1978-10-28	98	WC	Short record length
A42D	A4H008	Sterkstroom @ Doornspruit	-24.21686	27.9733	1964-08-21 2014-05-22	504	LP	
A61H	A6H027	Sterk River @ Doorndraai	-24.27573	28.77721	1953-03-01 2014-01-21	579	LP	Time series with zero flows (not perennial)
B11H	B1H002	Spookspruit @ Elandspruit	-25.819	29.33775	1956-10-09 2014-04-09	252	MP	
B11K	B1H004	Klipspruit @ Zaaihoek	-25.67364	29.17322	1959-02-08 2014-02-19	376	MP	
B83B	B8H011	Tsende River@Mooiplaas @ Kruger National Park	-23.52675	31.40351	1960-12-09 2014-02-01	432	LP	Time series with zero flows (not perennial river)
B90A	B9H001	Shisha River@Vlakteplaas @ Kruger National Park	-22.83843	31.23718	1960-08-28 2014-01-09	648	LP	Time series with zero flows (not perennial river)
B81D	B8H010	Letsitele River @ Mohlabas Location						
B42F	B4H005	Waterval River @ Modderspruit						
B42F	B4H021	Waterval River @ Buffelskloof	-24.95635	30.26785	1972-07-03 2014-03-10	278	MP	1991/12/05-1996/01/12 time series is unusually smaller than the rest

Catchment ID	River gauge	Station name and location	Latitude	Longitude	Period of record	Catchment area (km^2)	Province	Criteria
C11K	C1H005	Leeu Spruit @ Welbedacht	-26.85425	29.32531	1964-12-04 2014-03-27	341	MP	data with many gaps and Zero flows (majority)
C81F	C8H005	Elands River @ Elands River Drift	-28.37583	28.86028	1963-12-12 2014-01-22	696	FS	
C81J	C8H013	Vaalbank Spruit-West @ Vaalbank 327	-28.1075	28.78556	1971-11-27 2014-03-06	251	FS	Time series with zero flows (not perennial river)
C70G	C7H003	Heuning Spruit @ Dankbaar	-27.35611	27.28556	1947-11-01 2013-03-27	914	FS	Time series with zero flows (not perennial river)
V60B	V6H004	Sondags River @ Kleinfontein	-28.40486	30.0128	1954-01-01-2014-01-08	658	KZN	
T60K	T6H001	Mntafufu River @ Ntafufu Loc. 35	-31.49611	29.52881	1969-07-28-2014-05-12	108	EC	Gap in time series; e.g. 1979/08/22-1983/11/25 and1994/03/31-1997/09/17
H80A	H8H003	Duiwenhoks River @ Kliphoogte	-33.99694	20.94833	1964-01-21-2014-02-11	148	WC	Considerable gap in time series; 2003/01/28-2008/06/30
H40G	H4H018	Poesjenels River @ Le Chasseur	-33.86778	19.71611	1980-06-13-2014-02-17	252	WC	Time series b/n 1997/05/25-2003/02/05 is unusually smaller than the rest
K20A	K2H002	Great-Brak River @ Wolvedans	-34.02861	22.22194	1961-05-04-2014-03-05	131	WC	
K40B	K4H001	Hoekraal River @ Eastbrook	-33.97982	22.7995	1961-04-24-2014-06-03	22	WC	
K70B	K7H001	Bloukrans River @ Lotterings For.	-33.95556	23.63861	1961-06-05-2014-04-11	57	WC	

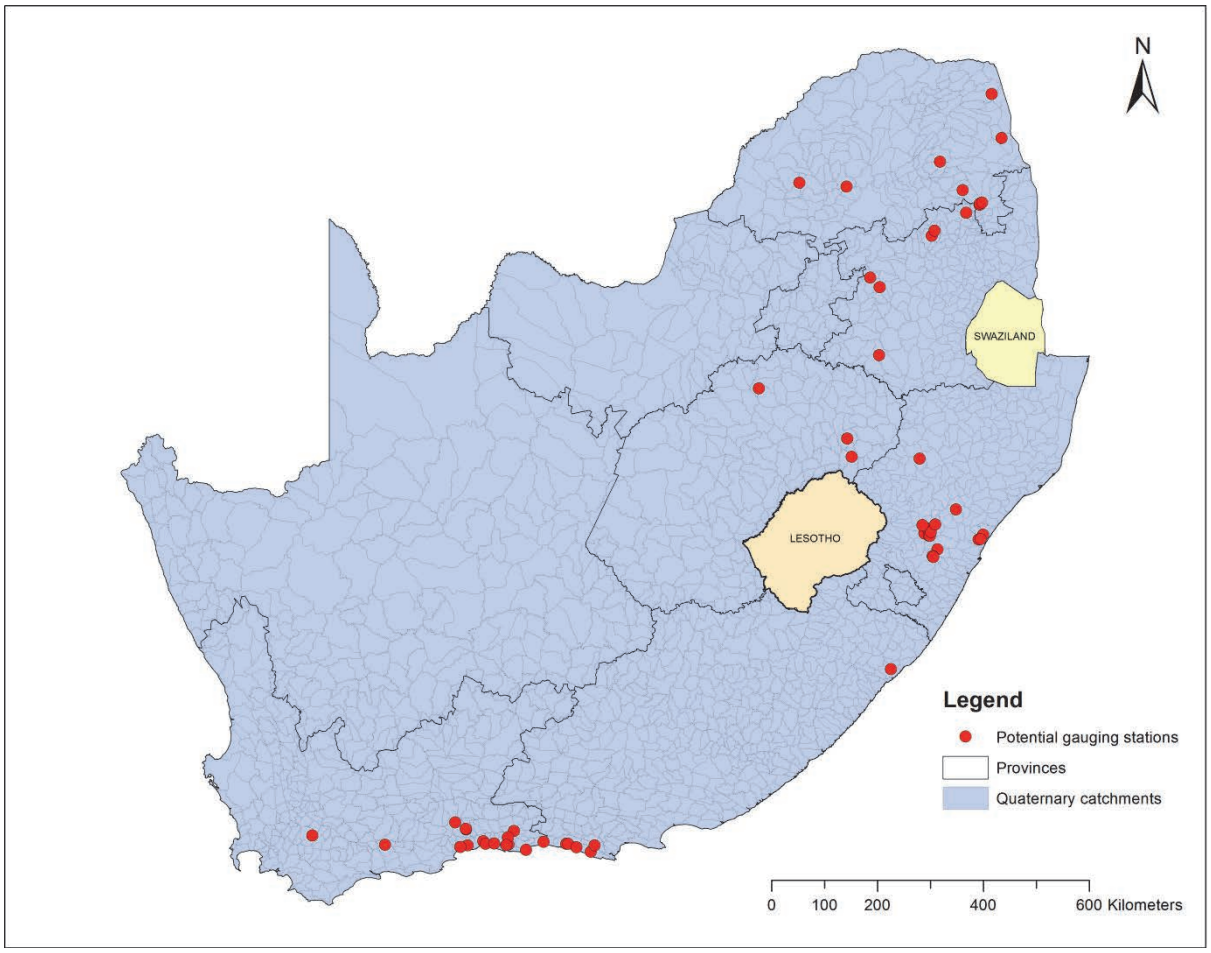

Figure 16: Potential gauging station locations (57 in total)

Annex2: Baseflow trend and change point analysis

A freely available trend/change detection software TREND V1.0.2 provided by eWater CRC (www.toolkit.net.au/trend) was used to facilitate statistical testing for trend and change point of time series data (Chiew and Siriwardend, 2005). The current version of the software can perform up to 12 statistical tests that can be used to test for trend, change point and randomness in hydrological and other time series data. In this study we used Mann-Kendall and distribution free CUSUM test to identify the trends and step jumps in annual baseflows. In the subsequent sections we provided detail descriptions of each method.

Mann-Kendall Trend Test

Mann-Kendall Trend test is a non-parametric, rank-based method for evaluating the presence of trends in time series data. The original algorithm was derived by Mann (1945) and Kendall derived the test statistic distribution (Abdi, 2007). The data are ranked according to time and then each data point is successively treated as a reference data point and is compared to all data points that follow in time. Compared to parametric statistical tests, non-parametric tests are advantages in the sense that the underlying probability distribution of the random variable need not be determined. Hence, non-parametric tests are suitable for non-normally distributed data which are frequently encountered in hydro-meteorological time series (Dou et al., 2009). Since the test statistics work based on the sign difference rather than on the magnitude of the data itself, it is less affected by the outlier of the data (Onoz and Bayazit, 2003). The Mann-Kendall test has two parameters that are of importance to the trend detection. These parameters are the significance level that indicates the trend's strength, and the slope magnitude estimate which indicates the direction as well as the magnitude of the trend. Equation 12-18 used to describe Mann-kendall test statics are extracted from Dou et al. (2009).

The Mann-Kendall test statistics is given by

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \qquad (12)$$

Where x_j and x_i are the sequential data values, n is the data set record length, and

$$\operatorname{sgn}(\theta) = \begin{cases} +1 & \theta > 0 \\ 0 & \theta = 0 \\ -1 & \theta < 0 \end{cases} \qquad (13)$$

For independent, identically distributed random variables with no tied data values, the expected mean is equal to zero (Equation 14) and the variance is calculated using Equation 15. When some data values of a given time series are equal correction to the calculated variance is applied using Equation 16. Based on the calculated sum of the sign difference and variance the test statics for the time series is computed using Equation 17. Sen's estimate for slope presented in Equation 18 is used to compute the magnitude and strength of the slopes.

$$E(\mathrm{S}) = 0 \qquad (14)$$

$$Var\,(\mathrm{S}) = \frac{\mathrm{n}\,(\mathrm{n}-1)\,(2\mathrm{n}-5)}{18} \qquad (15)$$

When some data values are tied, the correction to Var (S) is

$$Var\,(\mathrm{S}) = \frac{\mathrm{n}\,(\mathrm{n}-1)\,(2\mathrm{n}-5) - \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{t}_{\mathrm{i}}(i)\,(\mathrm{i}-1)\,(2\mathrm{i}-5)}{18} \qquad (16)$$

Where t_{i} denotes the number of ties of extent i. For n larger than 10, the test statistic

$$Z_S = \begin{cases} \dfrac{S-1}{[\mathrm{var}\,(\mathrm{S})]^{0.5}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{[\mathrm{var}\,(\mathrm{S})]^{0.5}} & S < 0 \end{cases} \qquad (17)$$

Sen's estimate for slope is associated with the Mann-Kendall test is computed using Equation 18.

$$\beta = \mathrm{Median}\left(\frac{\mathrm{x_j} - \mathrm{x_i}}{j-i}\right), \forall \mathrm{j} > \mathrm{i} \qquad (18)$$

A positive value of β indicates an upward trend, where as a negative value represents a downward trend.

Distribution free CUSUM Test

Distribution-free CUSUM test is a rank-based test in which successive observations are compared with the median of the sereis (McGilchrist and Woodyer, 1975). It is a non-parametric test that does not require any assumption about the form of distribution that the data derive from, e.g. there is no need to assume data are normally distributed (Kundzewicz and Robson, 2004; Taylor, 2000). The test statitisc for the distribution-free CUSUM is the maximum cumulative sum of the signs of the difference from the median starting from the beginning of the sereis. Given a time sereis of data (x_1, x_2, x_3, x_4……x_n) the test statitics is calaulated using Equation 19. The sign of the difference of each individual measrument from the media is decided based on Equation 20.

$$V_k = \sum_{i=1}^{k} \mathrm{sgn}\,(x_i - \mathrm{x}_{\mathrm{median}}) \qquad (19)$$

Where x_i is the sequential data values, $\mathrm{x}_{\mathrm{median}}$ is the sample median, n is the data set record length and K =1, 2, 3… n

$$\mathrm{sgn}\,(x) = \begin{cases} +1 & x > 0 \\ 0 & x = 0 \\ -1 & x < 0 \end{cases} \qquad (20)$$

The distribution of V_k follows the Kolmogorov-Smirnov two-sample statistics (KS = (2/n) max $|V_k|$(Chiew and McMahon, 1993; McGilchrist and Woodyer, 1975). Chiew and Siriwardend, (2005) used Equations 21 to calculate the critical values of max $|V_k|$.

$$V_{critical} = \begin{cases} 1.22\sqrt{n} & \alpha = 0.1 \\ 1.36\sqrt{n} & \alpha = 0.05 \\ 1.63\sqrt{n} & \alpha = 0.01 \end{cases} \qquad (21)$$

Results of trend and step jump analysis in annual baseflow

Significant trends in annual baseflow were detected for seven stations, four of which had trends that were decreasing in direction and three stations show an increasing trend (Table 13). Figure 17-24 show trends detected in seven of the stations. Trend result shows some patterns in locations of stations with similar trend results were detected in river gauging stations located in the same geographic locations. CUMSUM test results also show that of the twenty-one gauges, two had significant step jumps.

Table 13: Results of trend and step jump analysis for annual baseflow

Quaternary catchment	**River gauge**	**Mann-Kendall** **Trend test**	**CUSUM** **Changing point test**
B81D	B8H010	NS (α =0.1)	NS (α =0.1)
A42D	A4H008	NS (α =0.1)	NS (α =0.1)
B73A	B7H004	**Decreasing trend**(α =0.1)	NS (α =0.1)
B42F	B4H005	NS (α =0.1)	NS (α =0.1)
B11K	B1H004	**Increasing trend** (α =0.1)	**Step jump** (α =0.1). Year of change 1995
C81F	C8H005	**Increasing trend** (α =0.1)	NS (α =0.1)
V60A	V6H004	NS (α =0.1)	NS (α =0.1)
U20D	U2H006	NS (α =0.1)	**Step jump** (α =0.1). Year of change 1967
U20B	U2H007	NS (α =0.1)	NS (α =0.1)
U20A	U2H013	NS (α =0.1)	NS (α =0.1)
U70A	U7H007	**Decreasing trend**(α =0.05)	NS (α =0.1)

K80C	K8H001	**Decreasing trend**(α =0.05)	NS (α =0.1)
K80C	K8H002	NS (α =0.1)	NS (α =0.1)
K70B	K7H001	NS (α =0.1)	NS (α =0.1)
K60A	K6H001	NS (α =0.1)	NS (α =0.1)
K50A	K5H002	NS (α =0.1)	NS (α =0.1)
K40B	K4H001	NS (α =0.1)	NS (α =0.1)
K40C	K4H002	NS (α =0.1)	NS (α =0.1)
K30D	K3H005	**Increasing trend** (α =0.1)	NS (α =0.1)
K30A	K3H003	NS (α =0.1)	NS (α =0.1)
K20A	K2H002	**Decreasing trend**(α =0.1)	NS (α =0.1)

NS=data show no statistically significant trend or step jump

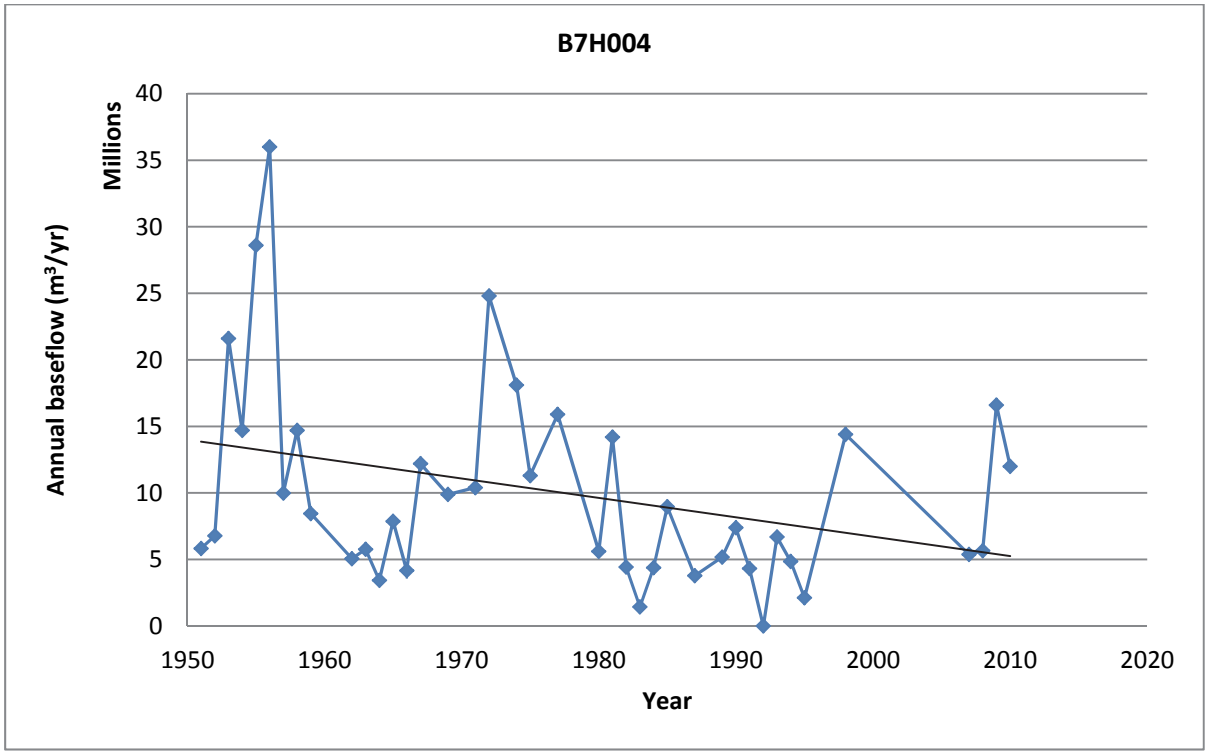

Figure 17: Annual baseflow trend for gauging station B7H004

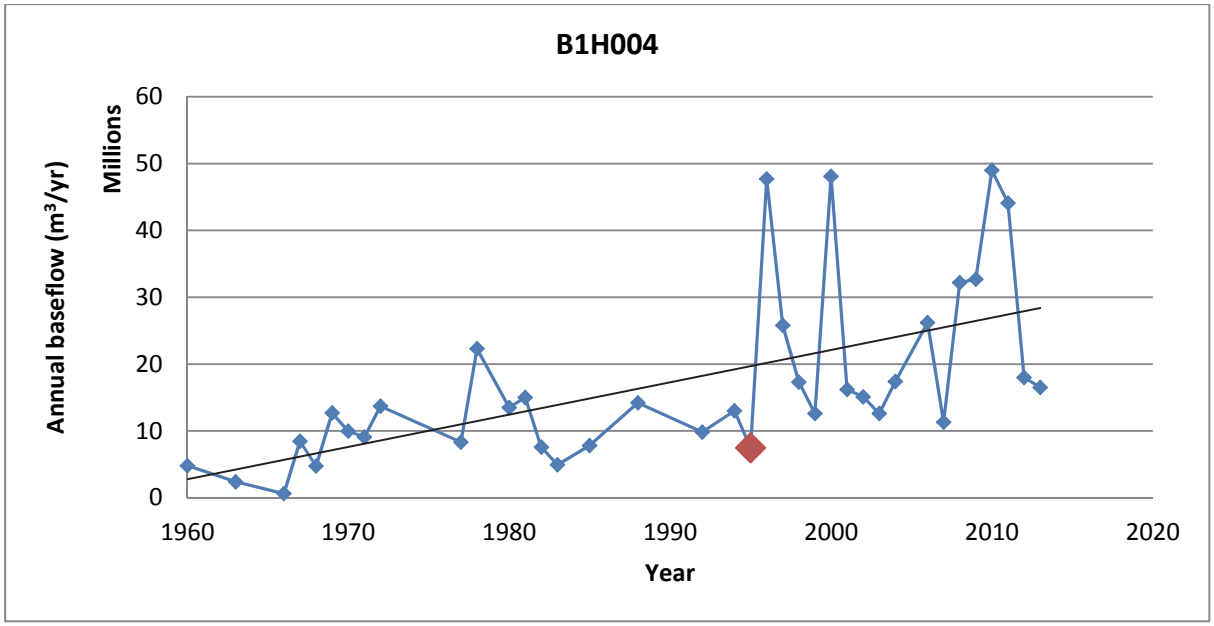

Figure 18: Annual baseflow trend and CUMSUM test for changing point for gauging station B1H004 (red diamond point indicates the location of the step jump)

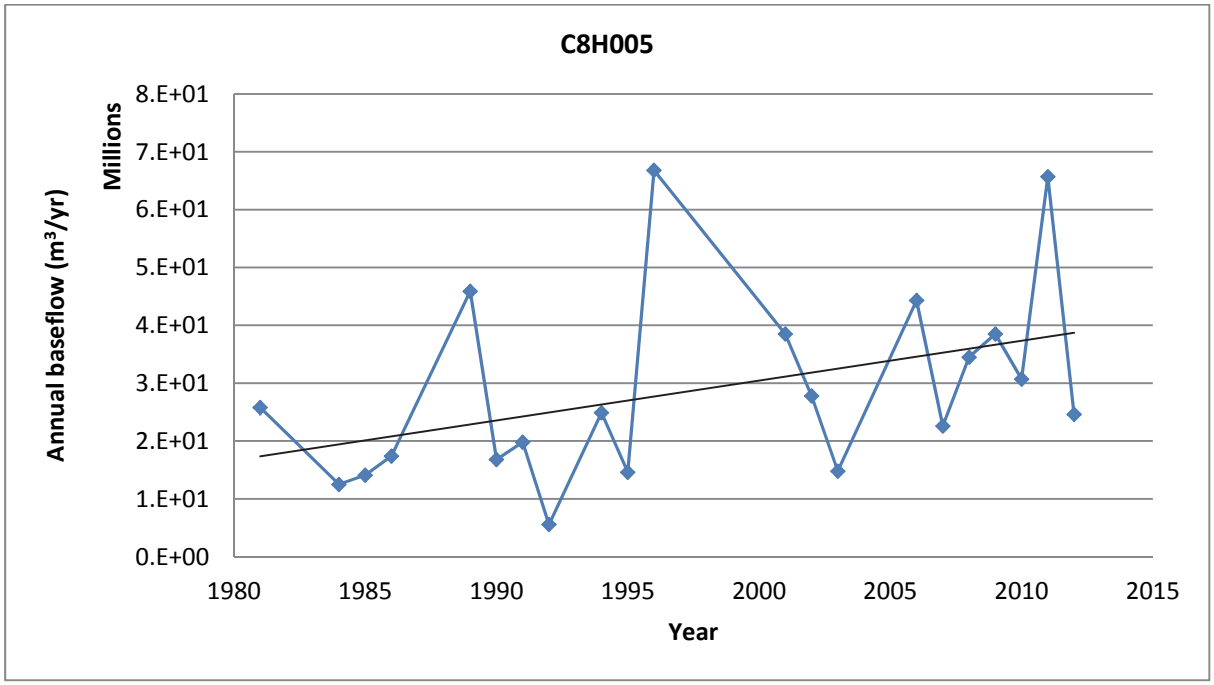

Figure 19: Annual baseflow trend for gauging station C8H005

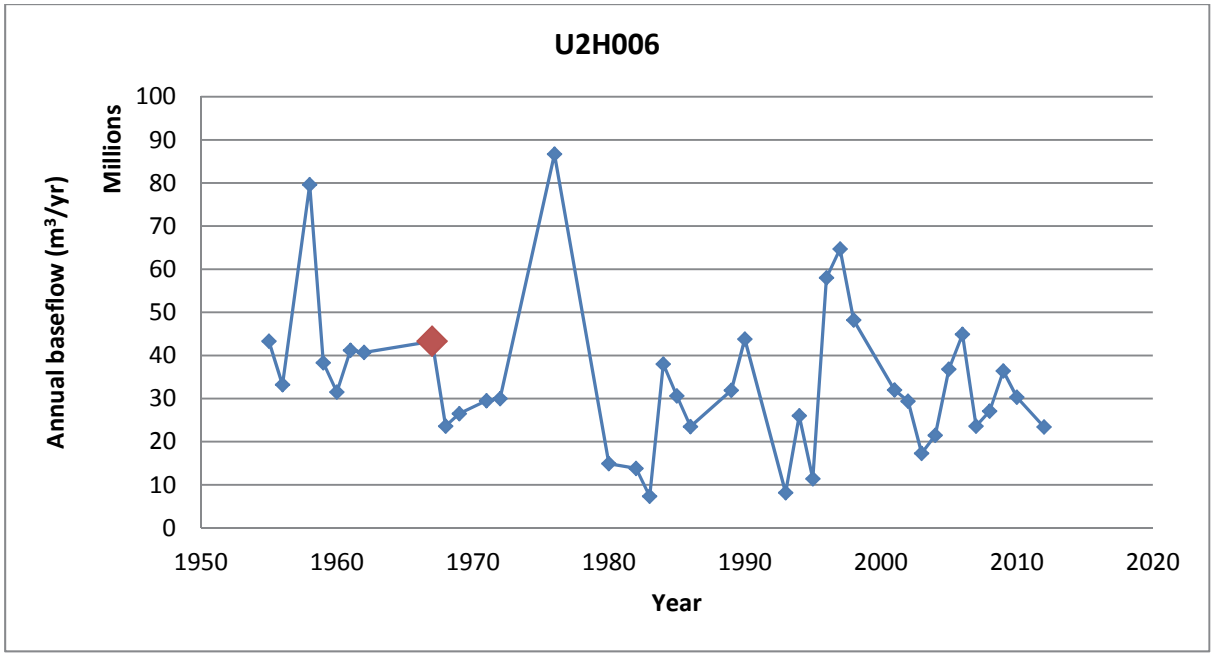

Figure 20: CUMSUM changing point test for gauging station U2H006 (red diamond point indicates the location of the step jump)

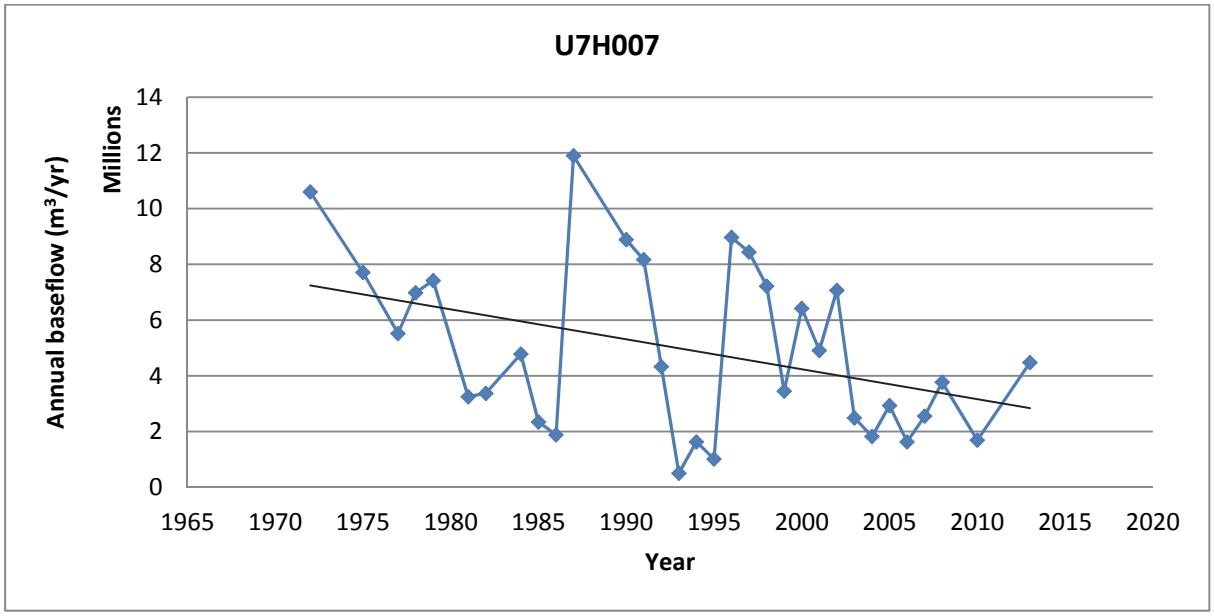

Figure 21: Annual baseflow trend for gauging station U7H007

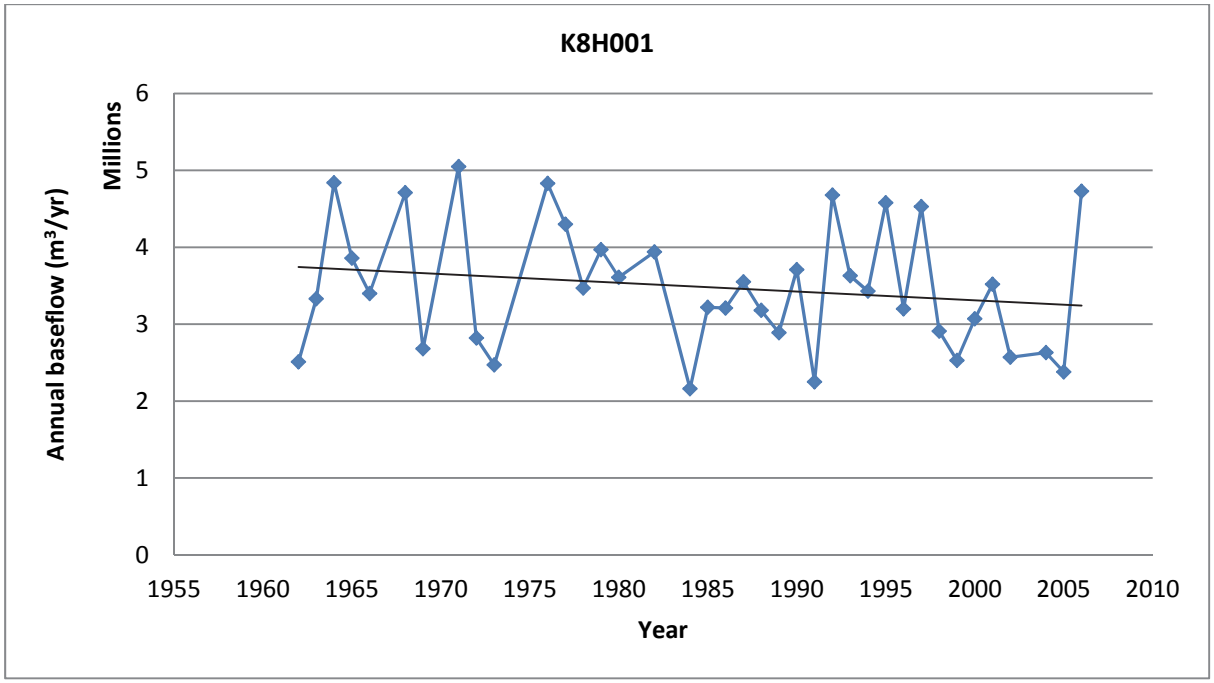

Figure 22: Annual baseflow trend for gauging station K8H001

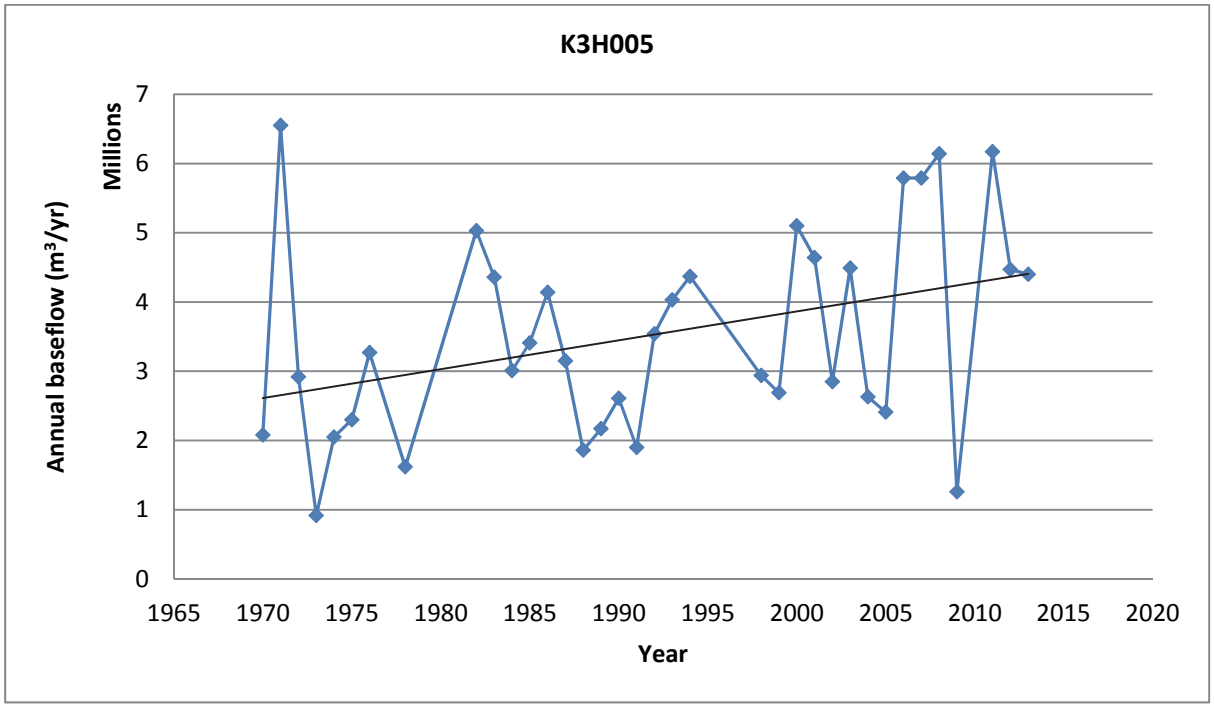

Figure 23: Annual baseflow trend for gauging station K3H005

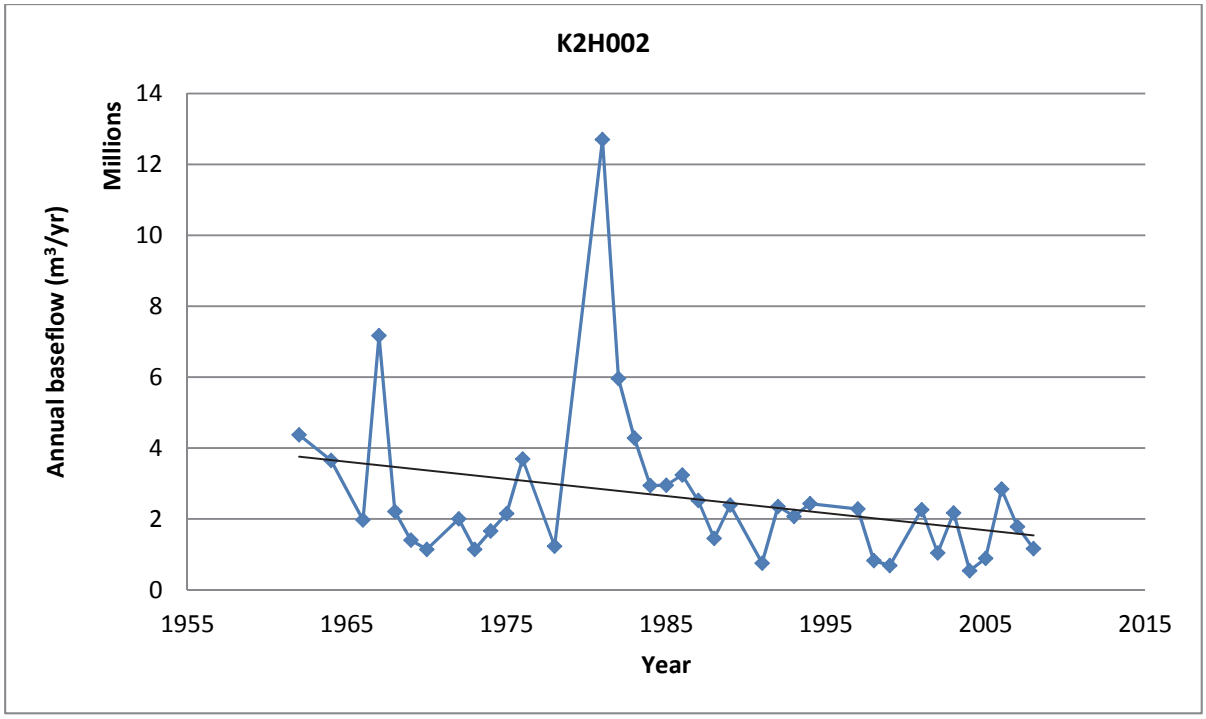

Figure 24: Annual baseflow trend for gauging station K2H002