*11th SAGA Biennial Technical Meeting and Exhibition*
*Swaziland, 16 - 18 September 2009, pages 565 - 570*

# Soil water saturation in the Cathedral Peak VI catchment, KwaZulu-Natal

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## ABSTRACT

Degree of water saturation and water storage capacity has been studied in the Cathedral Peak VI catchment in South Africa. Soil water content data for the Cathedral Peak VI collected since 1990 in various Water Research Commission projects were used to calculate the annual degree of water saturation (s) above 0.78 of porosity ($AD_{s>0.78}$) for the soils of the catchment. The $AD_{s>0.78}$ value was used to determine the soil water regime of soils of the catchment. The degree of water saturation (s) was found to be heterogeneous downslope in the catchment, controlled primarily by topography. Soils in the mid and upper slopes had a dry water regime while soils in the toe slope had a wetter water regime. The soil water storage capacity of the catchment was estimated to be approximately 248 583 $m^3$, using rainfall and streamflow data. Results reported here increases understanding of the hydrological characteristics of soils in the Cathedral Peak VI catchment and provide key information on the role of soils in catchment hydrology.

**Key words:** bulk density, critical zone, porosity, water saturation

## INTRODUCTION

The degree of water saturation of a soil (s) is defined as the fraction of the porosity that is occupied by water. This is considered to be a useful parameter due to its correlation with oxidation - reduction conditions in the soil. It was shown by Van Huyssteen *et al*. (2005) that for the Weatherley catchment high s-values (>0.7) for relatively long durations are generally associated with defined morphological signs (especially colour) of wetness. They refined the parameter to include a threshold value (fraction of porosity) and annual duration (AD) in days that the water content remained above the threshold value. They used the format, for example, $AD_{s>0.70}$ to indicate the average numbers of days per year that the water content of a particular soil layer was above 0.70 of saturation.

Soil water contents for Cathedral Peak VI measured by Everson *et al*. (1998) were used to calculate s-values for diagnostic horizons of the soils. The dataset included weekly soil water contents for 4 layers on 6 soil profiles, for the five-year period between 01 July 1997 and 30 June 2003. Results for selected profiles are presented here. All the data is expressed in terms of s-values. Expressing soil water content as s enables comparisons between different soils and facilitates pedological interpretation, especially redox reactions of the soils. Jennings (2007) found an s of 0.78 to be a suitable first approximation threshold value for the onset of significant reduction for a yellow brown apedal B horizon at Weatherley. This assumption is in line with the observation by Jenkinson *et al*. (2002) that reduction in a soil horizon begins before 100% saturation is attained, and progresses more rapidly as the horizon becomes more saturated. The $AD_{s>0.78}$ values were quantified as a hydropedological characteristic of these soils with the units of days per year. The duration of s>078 for a particular year is calculated as the number of days during the year the s was above 0.78 of porosity.

## METHOD AND RESULTS

The location of the sites at which Everson *et al*. (1998) made the neutron water meter readings used here are shown in Figure 1.

The Cathedral Peak VI catchment is situated in the Drakensberg mountains of the KwaZulu-Natal, between latitudes 28˚30'S and 30˚30'S and longitudes 28˚30'E and 29˚30'E. It forms part of the Cathedral Peak Forestry Research station which lies in the northern part of the crest, in a conserved area of the Natal Drakensberg Park. The catchment is 67.9 ha in extent and is moderately dissected by streams.

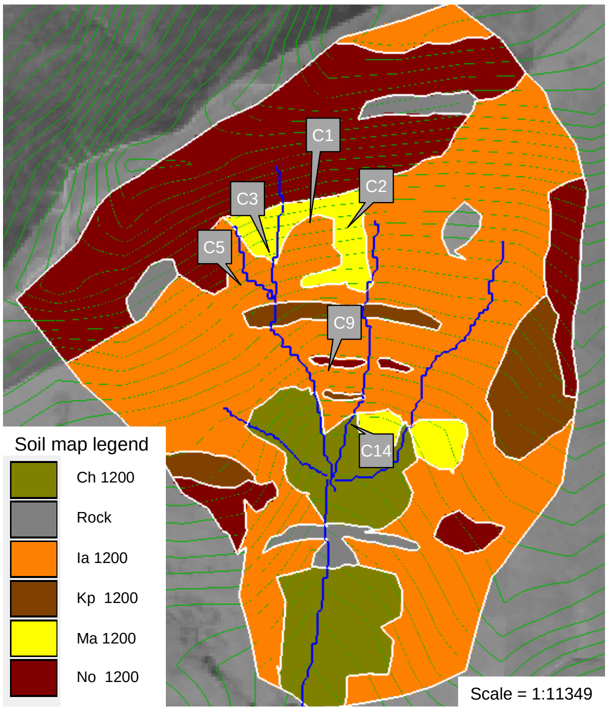


**Figure 1. Soil map (Kuenene, 2008) showing the position of the selected neutron water meter measuring sites (Everson *et al.*, 1998) on the Cathedral Peak VI catchment of 67.9 ha. (Ch = Champagne soil form, Ia = Inanda, Kp = Kranskop, Ma = Magwa, No = Nomanci, R = rock)**

The elevation range from 1 860 m above sea level at the weir to 2 070 m above sea level at the highest point. The terrain has a slope of 19% grading to 8% towards the outlet. Two large saturated zones exist in the catchment. The upper zone exists on a topographic convergence midway in the catchment and the other where the stream flattens before the catchment outlet (Everson *et al.*, 1998). The rainfall shows seasonal patterns. The mean annual rainfall for 5 years recorded at Cathedral Peak VI catchment is 1 299 mm. The selected soil profiles are situated on the east facing dominant hillslope of the catchment (Figure 1).

Calculation of degree of water saturation

The degree of water saturation (s) was calculated and used to determine annual duration of s in each diagnostic horizon:

$$s = \frac{V_w}{V_f} \quad (1)$$

Where:

s = degree of saturation (as a fraction)
$V_w$ = volumetric water content (mm $mm^{-3}$)
$V_f$ = total pore volume (mm $mm^{-3}$)

The total porosity (f) was calculated as follows (Hillel, 1982):

$$f = 1 - \frac{\rho_d}{\rho_s} \quad (2)$$

Where:

$\rho_d$ = bulk density (Mg $m^{-3}$)
$\rho_s$ = particle density (Mg $m^{-3}$)

Duration of s was calculated using the following equation (Van Huyssteen *et al.*, 2005):

$$AD_{s>0.78} = \sum_{s_n>0.78}^{year} DOY_n - DOY_{n-1} \quad (3)$$

Where:

$AD_{s>0.78}$ = duration of s above 0.78 of porosity (days $year^{-1}$)
$DOY_n$ = date of measurement
$DOY_{n-1}$ = date of previous measurement
s = degree of saturation
year = year (365 days)

Duration of s was calculated by adding the duration of individual s>0.78 events. An $AD_{s>0.78}$ event is defined as a measurement where s is in excess of 0.78 and s for the previous measurement is less than 0.78. This was based on the assumption that in the long-term, a particular measurement is representative of the soil water regime for the period between half way from the previous measurement that had s<0.78, to half way towards the following measurement which also had s<0.78. For consecutive measurements with s>0.78 the entire period was included when using the above equation.

Neutron access tube C1

The profile was classified as Inanda 1200 (Soil Classification Working Group, 1991) and is situated at the start of a 200 m downslope transect. The profile is situated in an upper midslope, with a slope of 19.2%. The rainfall and s-values in the humic A (125 mm) and red apedal B (875 mm) horizons shows a strong seasonal trend (Figure 2). The ET influence is visible in Figure 2 and far more marked at 125 mm compared to 875 mm due to more roots in the shallower layer.

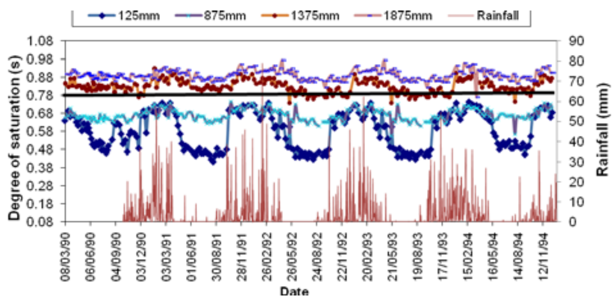


**Figure 2 Degree of saturation for the Inanda soil profile at C1 for the period August 1990 to November 1994 with associated rainfall.**

The water content (θ) in this profile is on average > 0.78 s in the saprolite at 1375 mm for 319 days $year^{-1}$ and at 1875 mm depth for 357 days $year^{-1}$ (Table 1). The profile was augered to 900 mm depth and no distinct morphological signs of wetness were detected within this depth. The absence of any morphological signs of wetness in the red apedal B horizon at 875 mm is well supported by the zero $AD_{s>0.78}$ values reported in Table 1 for this depth.

| Depth | Horizon | 90/91 | 91/92 | 92/93 | 93/94 | Mean | Std. dev |
|---|---|---|---|---|---|---|---|
| (mm) | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | | |
| 125 | ah | 0 | 0 | 0 | 0 | 0 | 0 |
| 875 | re | 0 | 0 | 0 | 0 | 0 | 0 |
| 1375 | so | 361 | 352 | 276 | 288 | 319 | 43 |
| 1875 | so | 365 | 365 | 359 | 348 | 357 | 8 |
| Rainfall (mm): 1 Oct-30 Sept | | 1223 | 1092 | 1093 | 1469 | | |

**Table 1. $AD_{s>0.78}$ for Inanda (C1) profile during 1990/91-1993/94 (ah = humic, re = red apedal, so = saprolite)**

The zero $AD_{s>0.78}$ values are, however, probably somewhat misleading because neutron water meter readings were generally only taken weekly, and presumably not during rain storms, or even soon afterwards. The zero values nevertheless show that generally any degree of wetness >0.78 s was short lived. It is clear that drainage was rapid.

Neutron access tube C2

The profile is situated in an upper midslope position, with a slope of 19.2%. The profile was classified as Magwa 1200 and is situated at 10 m downslope from C1. During dry months the humic A (125 mm) was drier than the underlying horizons. Like other profiles, this is according to the expectation, as the humic A, being the top horizon, undergoes the greatest net water loss due to ET during rain free winter months. This factor decreases in prominence in the deeper horizons.

This profile is saturated more than 0.78 s in the upper saprolite at 1 375 mm for 242 days year$^{-1}$ and for 293 day year$^{-1}$ in the lower saprolite at 1 875 mm (Figure 3 & Table 2).

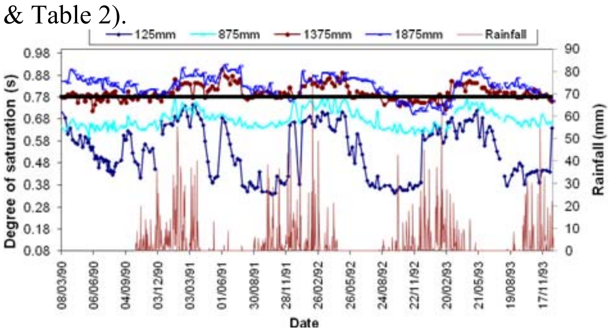


**Figure 3. Degree of saturation for the Magwa soil profile at C2 for the period March 1990 to November 1993 with associated rainfall.**

The profile was augered to 900 mm depth and no distinct morphological signs of wetness were observed within this depth, showing good agreement with the $AD_{s>0.78}$ values in Table 2.

| Depth | Horizon | 90/91 | 91/92 | 92/93 | Mean | Std. dev |
|---|---|---|---|---|---|---|
| (mm) | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | |
| 125 | ah | 0 | 0 | 0 | 0 | 0 |
| 875 | ye | 0 | 0 | 0 | 0 | 0 |
| 1375 | so | 261 | 292 | 172 | 242 | 51 |
| 1875 | so | 359 | 324 | 196 | 293 | 70 |
| Rainfall (mm): 1Oct-30 Sept | | 1223 | 1092 | 1093 | | |

**Table 2. ADs>0.78 for Magwa (C2) profile during 1990/91-1992/93 (ah = humic, ye = yellow brown apedal, so = saprolite)**

Neutron access tube C3

The profile is situated in an upper midslope position, with a slope of 19.1%. The profile was classified as Inanda 1200. A seasonal trend of rainfall and s values is evident in Figure 4 with s-values increasing during the rainy season, as expected, and decreasing during dry winter months. This is due to ET, which is prominent in the surface and less in the deeper horizons.

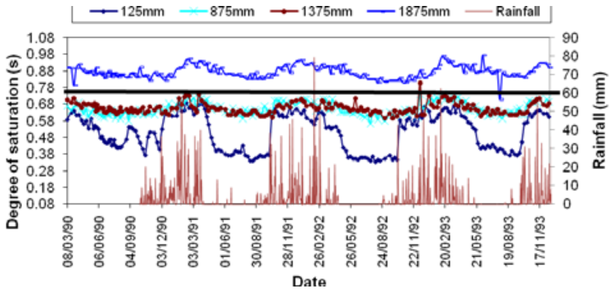


**Figure 4. Degree of saturation for the Inanda soil profile at C3 for the period March 1990 to November 1993 with associated rainfall.**

The mean $AD_{>0.78}$ values increase from a mere 3 days year$^{-1}$ in the red apedal B2 at 1375 mm to 358 day year$^{-1}$ in the saprolite at 1 875 mm (Figure 4 & Table 3). The profile was augered to a depth of 1 200 mm with no distinct morphological signs of wetness observed to this depth. As at C1 and C2 the results in table 4 show good agreement between the morphological features and $AD_{s>0.78}$ values.

| Depth | Horizon | 90/91 | 91/92 | 92/93 | Mean | Std. dev |
|---|---|---|---|---|---|---|
| (mm) | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | |
| 125 | ah | 0 | 0 | 0 | 0 | 0 |
| 875 | re | 0 | 0 | 0 | 0 | 0 |
| 1375 | so | 0 | 0 | 9 | 3 | 4 |
| 1875 | so | 362 | 365 | 350 | 358 | 5 |
| Rainfall (mm): 1 Oct-30 Sept | | 1223 | 1092 | 1093 | | |

**Table 3. $AD_{s>0.78}$ ($AD_{>0.78}$) for Inanda (C3) profile 1990/91-1992/93 (ah = humic, re = red apedal, so = saprolite)**

Neutron access tube C5C

The profile is situated in an upper midslope position, much closer to the stream than C1, C2, and C3 with a slope of 19.1%. The profile was classified as Inanda

1200. S-values decreased during dry winter months due to water loss by ET and drainage.

The mean $AD_{s>0.78}$ increased from 20 days year$^{-1}$ in the red apedal B1 at 875 mm to 84 days year$^{-1}$ in the red apedal B2 horizon at 1 375 mm depth and 360 days year$^{-1}$ in the saprolite at 1 875 mm (Figure 5 & Table 4).

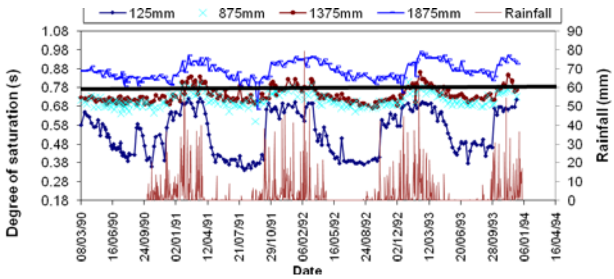


**Figure 5. Degree of saturation for Inanda soil profile at C5C for the period March 1990 to November 1993 with associated rainfall.**

Red, grey and black mottles of Fe and Mn were found at 1 875 mm depth in the saprolite, caused no doubt by the high $AD_{s>0.78}$ values promoting redox conditions. The high $AD_{s>0.78}$ value of 84 days year$^{-1}$ in the red apedal B2 horizon at 1 375 mm would also be expected to produce redoximorphic conditions. However, this was not the case. The reason for this anomaly is not clear. There are however, other factors that affect redox reactions which may have been operative here.

| Depth (mm) | Horizon | 90/91 | 91/92 | 92/93 | Mean | Std. dev |
|---|---|---|---|---|---|---|
| | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | |
| **125** | ah | 0 | 0 | 0 | 0 | 0 |
| **875** | re | 18 | 23 | 20 | 20 | 2 |
| **1375** | re | 65 | 92 | 94 | 84 | 13 |
| **1875** | so | 362 | 359 | 359 | 360 | 1 |
| Rainfall (mm): 1 Oct-30 Sept | | 1223 | 1092 | 1093 | | |

**Table 4. $AD_{s>0.78}$ ($AD_{>0.78}$) for Inanda (C5C) profile during 1990/91-1992/93 (ah = humic, re = red apedal, so = saprolite)**

Neutron access tube C9

The profile is situated in the lower midslope position, with a slope of 18%. The profile was classified as Inanda 1200. $AD_{s>0.78}$ decrease during dry winter months due to water loss by ET and drainage.

The mean $AD_{s>0.78}$ values increased from 58 days year$^{-1}$ in the red apedal B2 to 350 days year$^{-1}$ in the saprolite (Figure 6 & Table 5).

In this profile, red and black mottles of Fe and Mn were found in the red apedal B2 horizon at 1 375 mm and in the saprolite at 1 800 mm where grey mottles were also found.

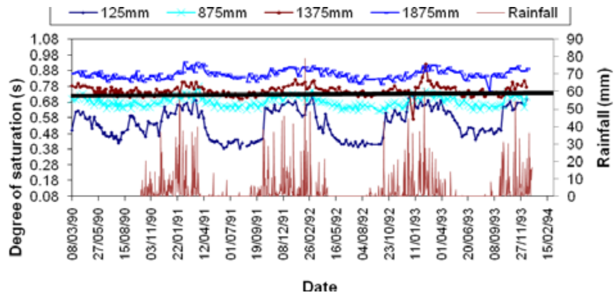


**Figure 6. Degree of saturation for the Inanda soil profile at C9 for the period March 1990 to November 1993 with associated rainfall.**

| Depth (mm) | Horizon | 90/91 | 91/92 | 92/93 | Mean | Std. dev |
|---|---|---|---|---|---|---|
| | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | |
| **125** | ah | 0 | 0 | 0 | 0 | 0 |
| **875** | re | 0 | 0 | 0 | 0 | 0 |
| **1375** | re | 34 | 78 | 63 | 58 | 18 |
| **1875** | so | 361 | 347 | 342 | 350 | 8 |
| Rainfall (mm): 1 Oct-30 Sept | | 1223 | 1092 | 1093 | | |

**Table 5. $AD_{>0.78}$ of the Inanda (C9) profile for 1990-93 (ah = humic, re = apedal, so = saprolite)**

Neutron access tube C14

The profile is situated in the low slope position, closer to the main stream, with a slope of 16.8%. The profile was classified as Inanda 1200 and is the last profile in a 200 m transect. The top horizon displays considerable variation throughout the years due to ET, as opposed to fairly constant wetness of the deeper horizons due to probably interflow of water from high lying soils.

This profile is saturated above 0.78 ($AD_{s>0.78}$) for 365 days year$^{-1}$ in the red apedal B1, the non diagnostic yellow brown apedal B2 horizon and in the saprolite (Figure 7 & Table 6).

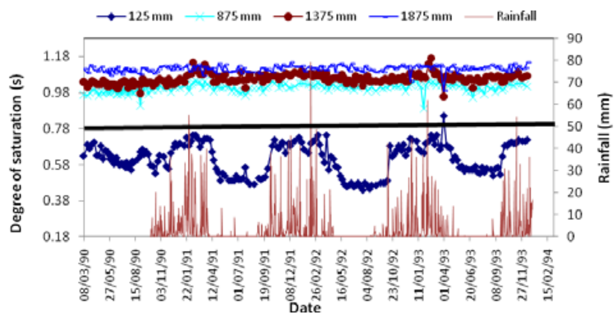


**Figure 7. Degree of saturation for Inanda soil profile at C14 for the period March 1990 to November 1993 with associated rainfall.**

It is not common to have these high $AD_{s>0.78}$ values for red apedal B horizons. This anomaly is not clear and warrants further scrutiny.

| Depth (mm) | Horizon | 90/91 | 91/92 | 92/93 | Mean | Std. dev |
|---|---|---|---|---|---|---|
| | | $AD_{s>0.78}$ (Days year$^{-1}$) | | | | |
| **125** | ah | 0 | 0 | 0 | 0 | 0 |
| **875** | re | 365 | 365 | 365 | 365 | 3 |
| **1375** | ye | 365 | 365 | 365 | 365 | 3 |
| **1875** | so | 365 | 365 | 365 | 365 | 3 |
| Rainfall (mm): 1Oct-30Sept | | 1223 | 1092 | 1093 | | |

**Table 6. $AD_{s>0.78}$ of Inanda (C14) profile during 1990/91-92/93 (ah = humic, re = red apedal, ye = yellow brown apedal, so = saprolite)**

A water table was encountered at 900 mm depth of the profile hence why the last two layers have s-values of almost 1 (Figure 7). Iron and manganese mottles were observed from 600 mm to 2 000 mm depth of the profile.

Estimating the storage capacity of the catchment

It has been observed from the hydrograph that a certain amount of rainfall is needed to fill the catchment before the hydrograph responds. This amount of rainfall was determined for each measurement year and converted into volumetric units ($m^3$) for the whole 67.9 ha catchment. The hydrograph was divided into appropriate portions and related to rainfall (Figure 8). For example, in the 1990/91 hydrological year, a total of 601 mm rainfall that was recorded for the 120 day period from 01/10/90 to 28/01/91 was enough to influence the significant response of the hydrograph (Symbol A1 in Figure 8). Evapotranspiration was deducted from this rainfall to determine effective rainfall for the period which was 294 mm. This was converted into volume ($m^3$) to estimate the storage capacity of the catchment (Table 7).

| Year | Effective rain until the hydrograph responds ($m^3$) | Drainage from the catchment during rain free (autumn & winter) periods ($m^3$) |
|---|---|---|
| 1990/91 | 199 920$^{A1}$ | 198 445$^{C1}$ |
| 1991/92 | | 108 179$^{C2}$ |
| 1992/93 | 158 508$^{A3}$ | 148 170$^{C3}$ |
| 1993/94 | 215 560$^{A4}$ | 248 583$^{C4}$ |

**Table 7. Rainfall and runoff data for the Cathedral Peak VI catchment used to estimate the storage capacity of the catchment. (*Effective rain= rainfall minus ET. A1, A3, A4, C1, C2, C3, C4 = symbols used in Figure 8)**

An alternative approach to calculate storage capacity is to determined amount of water drained out of the catchment during the dry season. If 199 920 $m^3$ of water filled the catchment storage to near saturation, then we can hypothesise that during rain free period (autumn & winter) amount drained until the next rain season is also an estimation of catchment storage capacity of the catchment. For the year 1990/91, the amount stored in the catchment will start to drain after rainy season (27/03/1991), to form a long recession (28/03/91-24/09/91) of the hydrograph (Figure 8). Amount drained for this period was calculated from the measured 1991 year record as 198 445 $m^3$. This estimate of the storage capacity is almost the same as the estimate based on the effective rainfall responsible for filling up the catchment. These estimated amounts and periods of storage capacity are shown in Figure 8. The volume of rainfall labelled as B1 in Figure 8, does not affect the estimates of storage capacity since this rain provides the runoff during the rain season. A hydrological year 1991/92 did not show clear storage estimation by rainfall (Figure 8) but given the estimates of other years, estimation by amount drained out of the catchment during rain free period can be achieved reliably. This is because estimations by rainfall and amounts drained out of the catchment during rain free periods agree well. It can be concluded that 1993/94 estimations represent close storage capacity of the catchment.

## CONCLUSIONS

The degree of saturation over 4 years in the Cathedral Peak VI catchment confirms soils of this catchment as freely drained in the upper horizon and less well drained in the lower lying saprolite. This is because most of the $AD_{s>0.78}$ values were higher in the saprolite of most of the profiles. A seasonal trend of rainfall and s-values was evident in all profiles with s-values increasing during the rainy season and decreasing during the dry winter months. This was due to evapotranspiration which was prominent in the surface horizons and less so in the deeper horizons. $AD_{s>0.78}$ correlated well with redoximorphic features observed in the soils. The water storage capacity of the catchment was estimated as 248 583 $m^3$. This is mainly because of the deep soils in the catchment and the good infiltration thereof as a result of the high organic matter content in the soils.

## ACKNOWLEDGMENTS

Dr Piet le Roux and various students who assisted in data collection, funding by the Water Research Commission, Mondi, North Eastern Cape Forests and the University of the Free State is gratefully acknowledged.

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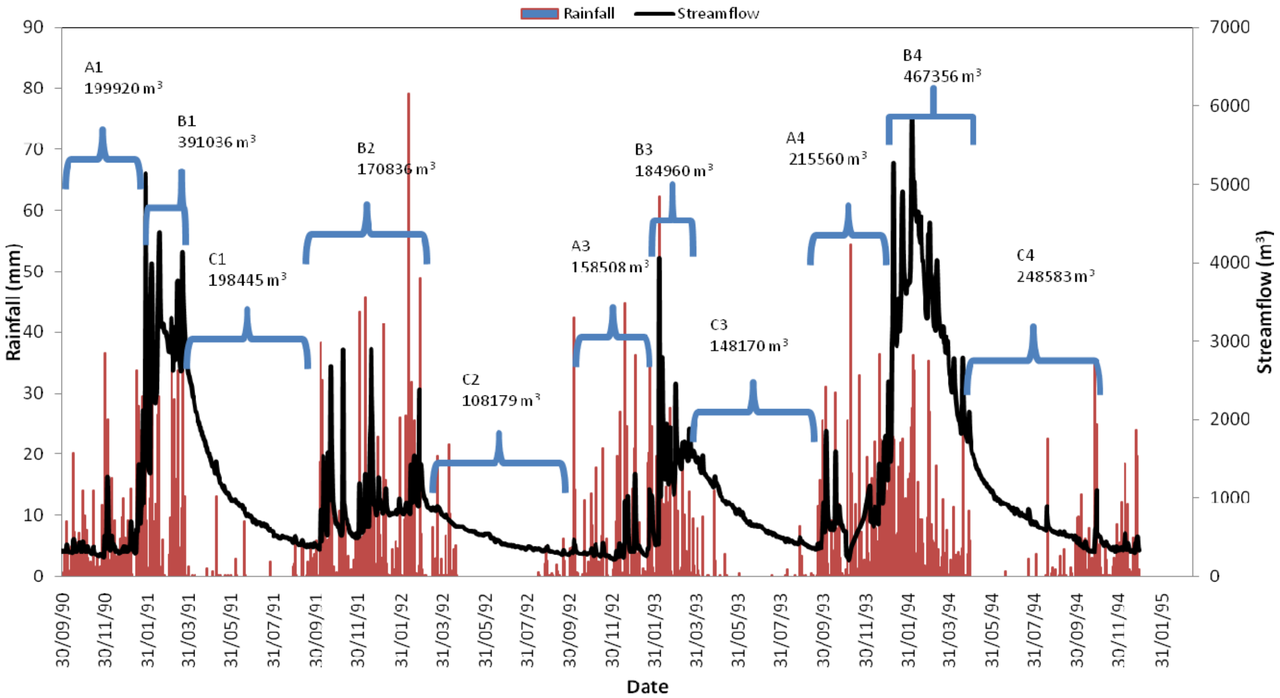


**Figure 8. Rainfall and hydrograph for the Cathedral Peak VI catchment for the period 30/9/1990-30/12/1994, subdivided into the following portions: A1, A3, A4 = rainfall until hydrograph responds; B1, B2, B3, B4 = rain that produces overland flow; C1, C2, C3, C4 = subsurface flow from the vadose zone during practically rain free autumn and winter months.**