Estimation of time parameter proportionality ratios in large catchments: case study of the Modder-Riet River Catchment, South Africa

C.E. Allnutt[1, 2] | O.J. Gericke[3] | J.P.J. Pietersen[4]

[1] Department of Civil Engineering, Tshwane University of Technology, Pretoria, South Africa
[2] Department of Civil Engineering, Central University of Technology, Free State, South Africa
[3] Department of Civil Engineering, Central University of Technology, Free State, South Africa
[4] Department of Civil Engineering, Central University of Technology, Free State, South Africa

Correspondence

Christopher Earl Allnutt, Department of Civil Engineering, Tshwane University of Technology, Staatsartillerie Road, Pretoria West, Pretoria, 0183, South Africa

Email: allnuttce@tut.ac.za

Funding information

National Research Fund, South Africa, Thuthuka Grant/Award
Reference: TTK160509164481
UID: 107199

Central University of Technology, Free State, South Africa, Postgraduate Grant/Award
Reference: 209016612

Abstract

Catchment response time parameters such as the time of concentration (T_C), lag time (T_L) and time to peak (T_P) are fundamental to design flood estimation in ungauged catchments; hence, errors in time parameter estimates directly impact on design flood estimates. The overall purpose of this study is to investigate and establish the suitability of the currently recommended time parameter definitions and proportionality ratios for small catchments in larger sub-catchment areas (exceeding 50 km²) of the Modder-Riet River Catchment (MRRC) in South Africa. The focus is on the estimation of time parameter proportionality ratios from observed rainfall and streamflow data using a simplified convolution process and the seven different time parameter definitions currently recognised in hydrological literature. Time parameters were individually estimated using the various time variables obtained from observed hyetographs and hydrographs to establish average time parameter proportionality ratios at a catchment level. The time parameter estimates proved to be highly variable due to the spatial and temporal distribution of rainfall events, variation in peak discharges and the distance of the rainfall events from the catchment outlet. However, the variability in the average estimated time parameter proportionality ratios proved to be less significant.

Keywords

Catchment response time; lag time; runoff; rainfall spatial distribution; South Africa; time of concentration; time to peak

1 INTRODUCTION

1.1 Analysis of hyetograph-hydrograph relationships

Understanding the nature of catchment response to rainfall input is at the core of applied hydrological applications, *e.g.* design flood estimation, water resources management, and catchment parameter estimation. Catchment response reflects how a catchment converts rainfall into runoff, and it incorporates the influence of numerous catchment characteristics, *e.g.* catchment geomorphology, channel geomorphology, soils, land-use and vegetation, and developmental and climatological variables. Catchment response is normally studied using a comparative analysis of the temporal and spatial characteristics of a rainfall hyetograph and the resulting streamflow hydrograph (Dingman, 2002). Indices such as the peak discharge, runoff volume, baseflow index, recession constant and response time could be obtained from rainfall hyetographs and streamflow hydrographs to provide first-order information to comprehend the rainfall-runoff relationship in a particular catchment (Dow, 2007; Elsenbeer & Vertessy, 2000; Ferguson & Suckling, 1990; Holton & Overton, 1963; Jones & Grant, 1996; Potter & Faulkner, 1987; Sujono *et al.*, 2004).

1.1.1 Time variables

Time variables can be estimated from the spatial and temporal distributions of rainfall hyetographs and streamflow hydrographs. To estimate these time variables, hydrograph analyses based on the separation of: (i) total runoff hydrographs into direct runoff and baseflow, (ii) rainfall hyetographs into initial abstraction, losses and effective rainfall, and (iii) the identification of the rainfall-runoff transfer function, are required. A complex process is used to transform the effective rainfall into direct runoff through a synthetic transfer function based on the principle of linear super-positioning, *e.g.* multiplication, translation and addition (Chow *et al.*, 1988; McCuen, 2005).

Effective rainfall hyetographs can be estimated from rainfall hyetographs in two separate ways, contingent upon whether observed data are available or not. In situations where both observed rainfall and streamflow data are available, index methods such as the: (i) Phi-index method, where the index equals the average rainfall intensity above which the effective rainfall volume equals the direct runoff volume, and (ii) constant-percentage method, where losses are proportionate to the rainfall intensity and the effective rainfall volume equals the direct runoff volume, can be used (McCuen, 2005). However, in ungauged catchments, the partitioning of rainfall losses should be based on infiltration methods, which account for infiltration and other losses individually. The Soil Conservation Service (SCS) runoff curve number (*CN*) method is internationally the most commonly used (Chow *et al.*, 1988).

In general, time variables obtained from hyetographs include the peak rainfall intensity, the centroid of effective rainfall and the end time of the rainfall event. Hydrograph-based time variables generally include the peak discharge, direct runoff, the centroid of direct runoff and the inflection point on the hydrograph recession limb (McCuen, 2009).

1.1.2 Time parameters

In considering observed rainfall and streamflow data in gauged catchments, time parameters are normally defined by the difference between two interrelated observed time variables (McCuen, 2009), which represent individual events on either a hyetograph or hydrograph. In small catchment areas (*A*) up to 50 km², the difference between two interrelated observed time variables is estimated using a simplified convolution process between a single rainfall hyetograph and resulting single-peaked hydrograph. In medium to large heterogeneous catchment areas, typically ranging from 50 km² to 35 000 km², a similar convolution process is required where the temporal relationship between a catchment rainfall hyetograph, which may be derived from numerous rainfall stations, and the resulting outflow hydrograph, is established (Gericke & Smithers, 2017).

The analysis of hyetograph-hydrograph relationships to obtain time variables and time parameters is often done manually, relying on visual examination and interpretation. As a result, considerable time is required to implement these analyses and in general, results could be regarded as inconsistent and subjective. In contrast, automated hydrograph analyses provide objective and consistent results (White & Sloto, 1990). Former automated tools for hydrograph analyses primarily focussed on the selection of hydrograph characteristics and the incorporation of baseflow separation, recession analyses and direct runoff estimation (Arnold *et al.*, 1995; Chapman, 1999; Lim *et al.*, 2005; Piggott *et al.*, 2005; Rutledge, 1998; Sloto & Crouse, 1996). However, the use of automated tools to extract and analyse rainfall hyetographs, is not common practice and most of the rainfall-based time variables are extracted manually. In essence, none of the automated tools developed include both rainfall hyetograph and streamflow hydrograph characteristics, while the relationship between rainfall-based and runoff-based time variables is not defined. Hence, the need to develop an automated tool for hyetograph-hydrograph analyses was identified as one of the specific objectives in this study.

1.2 Catchment response time estimation methods

Almost all design flood estimation methods require at least one time parameter, *e.g.* T_C, T_L and/or T_P as input. Traditionally, time parameters have numerous theoretical or computational definitions, and T_L is sometimes expressed in terms of T_C. Different researchers, *e.g.* Fang *et al.* (2008); Hood *et al.* (2007); Jena and Tiwari (2006); McCuen (2005; 2009); McCuen *et al.* (1984); Schmidt and Schulze (1984); Simas (1996), have utilised the difference between the corresponding values of time variables to define two unique time parameters, namely T_C and T_L. Apart from the latter two time parameters, other time parameters, *e.g.* T_P and the hydrograph time base (T_B) are also often considered.

In the following sections the theoretical definitions of T_C, T_L and T_P are detailed.

1.2.1 Time of concentration

Numerous definitions are documented in the literature to define T_C. The most commonly used, conceptual and physically-based definition of T_C is the time required for runoff, due to effective rainfall, with a uniform spatial and temporal distribution over a catchment, to contribute to the peak discharge at the catchment outlet. In other words, the time required for a 'water particle' to flow from the most remote catchment boundary along the longest watercourse to the catchment outlet (Kirpich, 1940; McCuen, 2005; McCuen *et al.*, 1984; SANRAL, 2013; USDA NRCS, 2010).

In utilising such a conceptual definition, the computational definition of T_C is accordingly the distance travelled along the principle flow path, which is partitioned

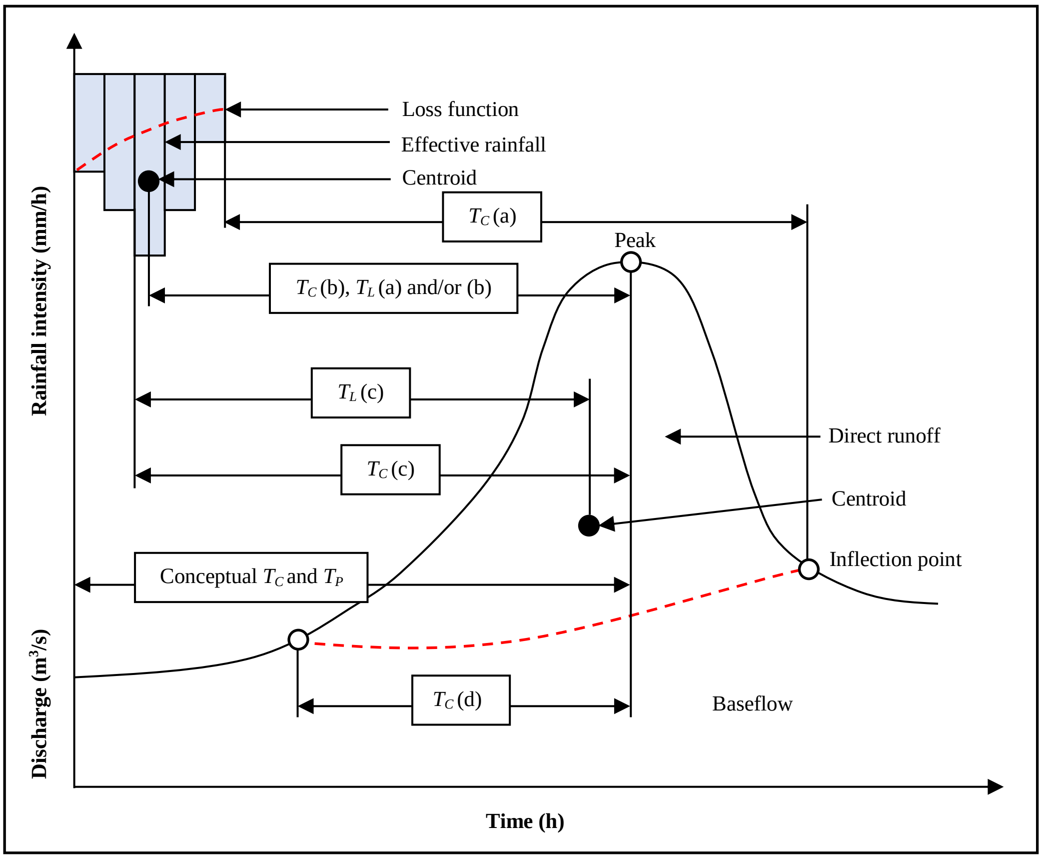

FIGURE 1: Schematic diagram illustrative of the different time parameter definitions and relationships (after Gericke & Smithers, 2014)

into sections of sensibly uniform hydraulic characteristics, divided by the average flow velocity in each of the sections (McCuen, 2009). The current common practice is to divide the principal flow path into sections of overland flow and principle conduit or channel flow, after which, the travel time in the various sections are computed separately and totalled. The second theoretical definition of T_C is related to the temporal distribution of rainfall and runoff, where T_C is characterised as the time between the start of effective rainfall and the resulting peak discharge. Various computational definitions have been proposed to estimate T_C from observed rainfall and runoff data. The following definitions, as illustrated in Figure 1, are occasionally used to estimate T_C from observed hyetographs and hydrographs (McCuen, 2009):

(a) The time from the end of effective rainfall to the inflection point on the hydrograph recession limb, *i.e.* the end of direct runoff; however, this is also the definition used by Clark (1945) to define T_L;
(b) The time from the centroid of effective rainfall to the peak discharge; however, this is also the definition used by Snyder (1938) to define T_L;
(c) The time from the maximum rainfall intensity to the peak discharge; or
(d) The time from the start of direct runoff (rising limb of hydrograph) to the peak discharge.

In South Africa, the South African National Roads Agency Limited (SANRAL) endorses the use of T_C definition (d) (SANRAL, 2013), but in principle all these definitions are reliant on the conceptual definition of T_C. It is also important to note that all the definitions listed in (a) to (d) are based on time variables with an associated probability distribution or degree of uncertainty. The centroid values denote 'average values' and are therefore deemed to be more stable time variables representative of the catchment response, especially in larger catchments where flood volumes are central to the design (McCuen, 2009). In comparison to large catchments, the time variables associated with peak rainfall intensities and peak discharge are regarded as the best estimate of the catchment response in smaller catchments where the exact occurrence of the peak discharge is of more significance.

McCuen (2009), analysed 41 hyetograph-hydrograph datasets from 20 catchment areas ranging from 1 to 60 ha in the United States of America (USA). The results from floods estimated using the Rational and/or NRCS TR-55 methods signified that the T_C based on the conceptual definition and principal flow path characteristics considerably underestimate the temporal distribution of runoff, and that T_C should be increased with a factor of 1.56 in order to correctly reflect the timing of runoff from the entire catchment, while the T_C based on T_C definition (b), proved to be the most accurate and was therefore recommended.

1.2.2 Lag time

Theoretically, T_L is generally described as the time between the centroid of effective rainfall and the peak discharge of the resultant hydrograph, which is the same as T_C definition (b) as shown in Figure 1. T_L can be estimated as a weighted T_C value when, for a given rainfall event, the catchment is separated into sub-areas and the travel times from the centroid of each sub-area to the catchment outlet are determined (USDA NRCS, 2010).

In flood hydrology T_L is generally estimated using either empirical or analytical techniques to establish the correlation between the response time and meteorological and geomorphological parameters of a catchment. Hydrological literature frequently fails to clearly differentiate between T_C and T_L, particularly when observed data (hyetographs and hydrographs) are used to estimate these time parameters. The variations between time variables from numerous points on the hyetographs to numerous points on the resultant hydrographs are sometimes misconstrued as T_C.

The following definitions, as illustrated in Figure 1, are used to estimate T_L from observed hyetographs and hydrographs (Heggen, 2003):

(a) The time from the centroid of effective rainfall to the time of the peak discharge of direct runoff;
(b) The time from the centroid of effective rainfall to the time of the peak discharge of total runoff; or
(c) The time from the centroid of effective rainfall to the centroid of direct runoff.

As in the case of T_C, T_L is also based on uncertain and inconsistent time variables. Nevertheless, the T_L definitions (a) to (c) detailed above are based on centroid values and are therefore regarded as more stable time variables illustrative of the catchment response time in larger catchments. Pullen (1969) also highlighted that T_L is favoured as a measure of catchment response time, particularly due to the integration of storm duration in the different definitions. Definitions (a) to (c) are commonly used to define T_L, *e.g.* Folmar and Miller (2008); Hood *et al.* (2007); Pavlovic and Moglen (2008); Simas (1996), despite of the fact that T_L definition (b) is occasionally also used to define T_C.

Due to the difficulty in estimating the centroid values of hyetographs and hydrographs, alternative T_L estimation techniques have been proposed in literature. Instead of utilising T_L as an input for design flood estimation methods, it is preferably utilised as input to the computation of T_C. In using T_L definition (c), T_C and T_L are related by $T_C = 1.417T_L$ (McCuen, 2009). In T_L definitions (a) and (b), the proportionality ratio increases to 1.667 (McCuen, 2009). However, in contradiction to above-mentioned proportionality ratios, Schultz (1964) demonstrated that $T_L \approx T_C$ in small catchments in Lesotho and South Africa.

1.2.3 Time to peak

The T_P, which is utilised in numerous hydrological applications, can be defined as the time from the beginning of effective rainfall to the peak discharge in a single-peaked hydrograph (Linsley *et al.*, 1988; McCuen *et al.*, 1984; Seybert, 2006; USDA SCS, 1985). However, this is also the theoretical definition used for T_C (*cf.* Figure 1). T_P is likewise in some cases characterised as the time interval between the centroid of the effective rainfall and the peak discharge of direct runoff (Heggen, 2003); however, this is also one of the definitions used to define T_C and T_L utilising T_C definition (b) and T_L definition (c), respectively. As indicated by Ramser (1927), T_P is considered to be synonymous with T_C and both these time parameters are reasonably constant for a particular catchment. In contrast, Bell and Kar (1969) demonstrated that these time parameters are not constant and vary in the range of between 40% and 200% from the median value.

1.3 Application of time parameters in design flood estimation

In ungauged catchments, catchment response time parameters are estimated utilising either empirically or hydraulically-based methods; however, analytical or semi-analytical methods are also occasionally used (McCuen, 2009; McCuen *et al.*, 1984). Empirical methods are commonly used by practitioners to estimate the catchment response time and almost 95% of all the methods developed internationally, are empirically-based (Gericke & Smithers, 2014). Conversely, most of these methods are related to and calibrated for small catchments, with only the research of Thomas *et al.* (2000) applicable to catchment areas of up to 1 280 km² and the research of Johnstone and Cross (1949); Mimikou (1984); Pullen (1969); Watt and Chow (1985), and Sabol (2008) focussing on larger catchments of up to 5 000 km².

Regrettably, in South Africa none of the empirical T_C estimation methods suggested for general use was developed and calibrated using local data. In small, flat catchments with overland flow being dominant, the use of the Kerby equation (Kerby, 1959) is suggested, while the empirical United States Bureau of Reclamation (USBR) equation (USBR, 1973) is utilised to estimate T_C as channel flow in a defined watercourse (SANRAL, 2013). Both the Kerby and USBR equations were developed and calibrated in the USA for catchment areas less than 4 ha and 45 ha, respectively (McCuen *et al.*, 1984). Thus, practitioners in South Africa commonly apply these 'recommended methods' beyond their limits, both in terms of spatial extent and their original developmental regions, without using any local correction factors (Gericke & Smithers, 2014).

The empirical estimates of T_L utilised in South Africa are constrained to the group of equations developed by the Hydrological Research Unit (HRU; Pullen, 1969); the United States Department of Agriculture Natural Resource Conservation Service (USDA NRCS), previously known as the USDA Soil Conservation Service (USDA SCS, 1985) and SCS-SA (Schmidt & Schulze, 1984) equations. Both the HRU and Schmidt-Schulze T_L equations were locally developed and calibrated. The HRU methodology is prescribed for catchment areas less than 5 000 km², while the Schmidt-Schulze (SCS-SA) methodology is restricted to small catchment areas less than 30 km².

The SCS-Mockus method is the only empirical method used in South Africa to estimate T_P based on the Synthetic Unit Hydrograph (SUH) research led by Snyder (1938), while Mockus (1957; cited by Viessman *et al.*, 1989) developed the SCS SUHs from dimensionless unit hydrographs, as acquired from numerous hydrographs in catchments of different sizes and geographical localities.

In using event-based deterministic design flood estimation methods in ungauged catchments, T_C, T_L and T_P are generally used to estimate the catchment response time. T_C is not only the most commonly used time parameter in event-based design flood estimation methods (Gericke & Smithers, 2014; SANRAL, 2013), but it is also applied in continuous simulation modelling, *e.g.* Neitsch *et al.* (2005); Smithers *et al.* (2013); USACE (2001). T_C is primarily used to estimate the critical storm duration of a particular design rainfall event which serves as input to deterministic methods, *i.e.* the Rational and Standard Design Flood (SDF) methods, while T_L is utilised as input to the deterministic SCS and SUH methods.

The concurrent use of the various time parameter definitions and proportionality ratios as recommended in the literature, as well as the inherent procedural limitations of the traditional simplified convolution process when applied in medium to large catchments, combined with the absence of both continuously recorded rainfall data and available direct measurements of rainfall and runoff relationships at these catchment scales, has not just curtailed the establishment of objective time parameter estimation procedures in South Africa, but also had a direct impact on design flood estimation (Gericke, 2016).

2 STUDY AREA

2.1 Location and general characteristics

South Africa is demarcated into 22 primary drainage regions, which are further sub-divided into 148 secondary drainage regions. The MRRC comprises of the C5 secondary drainage region located within primary drainage region C (Midgley *et al.*, 1994). The MRRC covers 34 795 km^2 and is located between 28°25' and 30°17' S and 23°49' and 27°00' E (DWAF, 1995). The Modder and Riet Rivers are the principal river reaches in the MRRC and discharge into the Orange-Vaal River drainage system (Midgley *et al.*, 1994).

The native vegetation consists of Grassland of the Interior Plateau, False Karoo and Karoo. Agricultural land is the largest human-induced modification in the rural areas, while residential and suburban areas govern the urban areas (CSIR, 2001). Practically, 99.1% of the MRRC comprises of rural areas, while 0.7% and 0.2% denote urban areas and water bodies, respectively (DWAF, 1995). The landscape is gentle with slopes between 2.4 and 5.5% (USGS, 2016), while water has a tendency to pool easily; hence, affecting the attenuation and translation of floods.

In the MRRC, the average Mean Annual Precipitation (MAP) is 424 mm, varying from 275 mm in the west to 685 mm in the east (Lynch, 2004). The rainfall is primarily classified as convective rainfall, which is regarded as highly variable in both time and space. The rainy season commences in early September and ends in mid-April with a dry winter.

2.2 Rainfall monitoring network

There are 185 South African Weather Services (SAWS) daily rainfall stations located within the boundaries of the MRRC. However, currently, there are only 40 active SAWS rainfall stations available in the MRRC, while only 169 SAWS rainfall stations, as shown in Figure 2, proved to have adequate historical data both in terms of record length and data quality to conduct this study. It is apparent from the rainfall monitoring network in Figure 2 that it is more condensed in the mid-eastern parts than in the north-western parts of the MRRC (Pietersen, 2016).

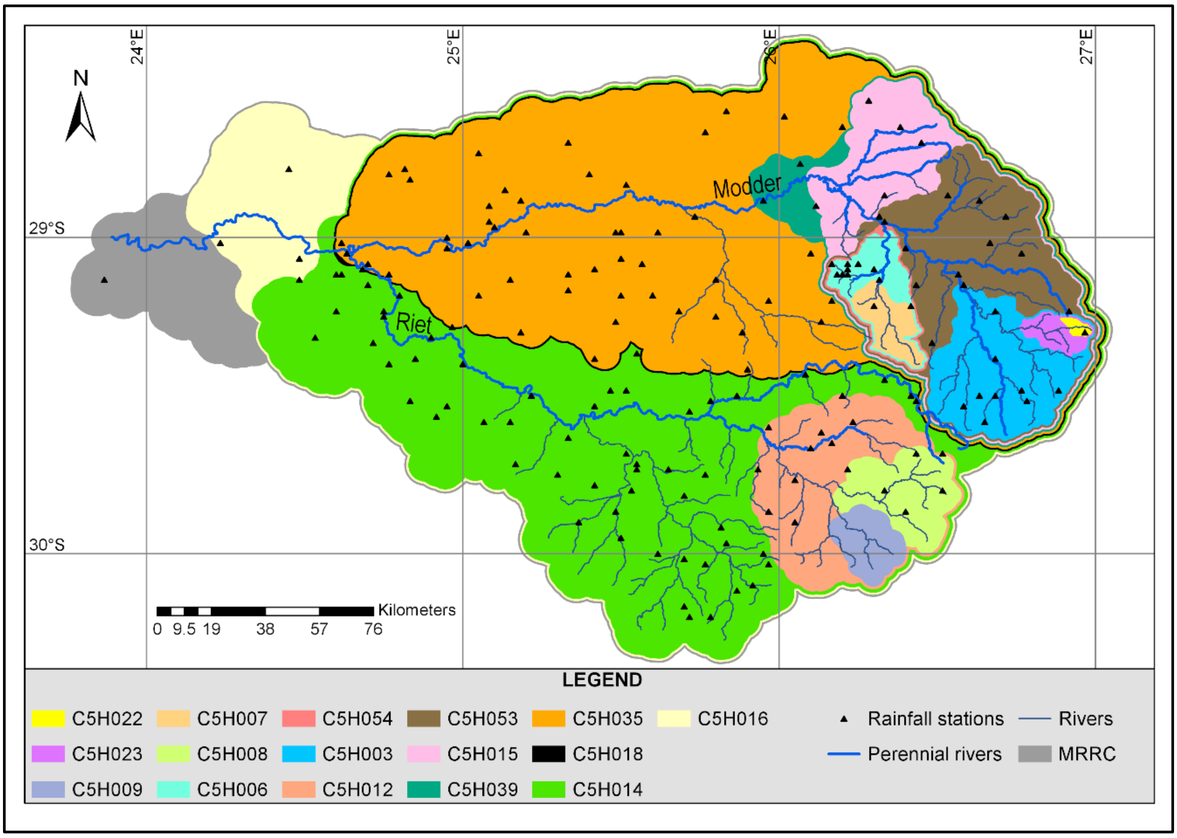

FIGURE 2: Location of the daily SAWS rainfall stations within the sub-catchments of the MRRC

2.3 Flow gauging network

There are 16 gauged sub-catchment areas ranging between 39 km^2 and 33 278 km^2 in the MRRC. The sub-catchments are regarded as 'gauged', since Department of Water and Sanitation (DWS) flow-gauging stations are located at the outlet of each sub-catchment. The layout of each sub-catchment, the river network and location of each individual flow-gauging station are shown in Figure 3.

3 METHODOLOGY

3.1 Establishment of rainfall database

A daily rainfall database was established by evaluating, preparing and extracting daily rainfall data from the SAWS and the Agricultural Research Council - Institute for Soil, Climate and Water (ARC-ISCW) rainfall stations present in the MRRC. In total, 169 rainfall stations were used due to a lack of data from 16 stations within the MRRC.

The Daily Rainfall Extraction Utility (DREU; Lynch, 2004) was used for the extraction of all the daily rainfall data series. Infilling of missing rainfall data to extend the rainfall data series was not considered. In cases where inactive SAWS rainfall stations lacked data, data from the ARC-ISCW database were combined with the SAWS database as far as possible to extend the rainfall data series. The ARC-ISCW stations used to extend the data series of inactive SAWS stations were in close proximity to the inactive stations. A list of all 169 SAWS rainfall stations with coordinates were sent to the ARC-ISCW. The ARC-ISCW only found 35 stations that were in close proximity to the 35 SAWS rainfall stations. In other words, this denoted that only the data series from 35 stations out of the 169 SAWS stations could be extended.

The Geographical Information Systems (GIS) feature classes (shape files) containing the spatial features of the complete daily rainfall database were generated in the ArcGIS™ 10.1 environment. During the analyses, care was taken to ensure that all the stations within a sub-catchment contributed to the rainfall data. In cases where missing rainfall data are present during the analyses, the Automated Toolkit developed (*cf.* Section 3.3), would caution the user about the presence of a negative Phi-index and that an alternative rainfall-runoff event needs to be selected.

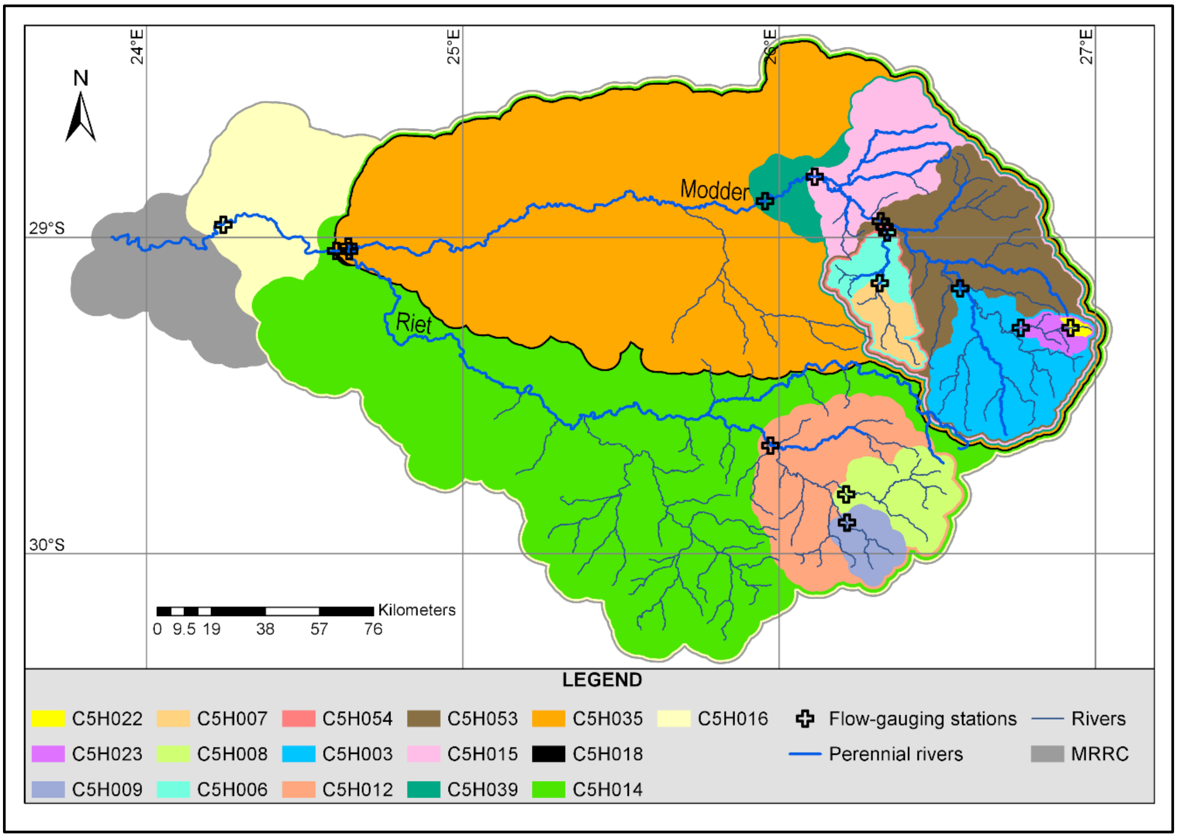

FIGURE 3: Location of the DWS flow-gauging stations and sub-catchments in the MRRC

3.1.1 Synchronisation of rainfall data

The degree of synchronisation between the point rainfall data sets at each rainfall station was established by considering recorded rainfall with mutual time intervals. The rainfall data series at each rainfall station was firstly exported and converted to a Microsoft Excel file format (*e.g.* *.xlsx). Thereafter, the rainfall data files were imported to the Automated Toolkit (*cf.* Section 3.3). In essence, a number of logic and synchronisation functions are available in the Visual Basic for Applications (imbedded in Microsoft Excel) environment to enable the automatic synchronisation of daily rainfall data, *e.g.* 'INDEX' and 'MATCH'. The use of the Automated Toolkit ensured that large data sets from numerous rainfall stations within a particular sub-catchment could be synchronised within minutes.

3.1.2 Averaging of observed rainfall data

In the calculation of total quantities of rainfall over large areas, the frequency of storms and their contribution to single rainfall stations is unknown. Therefore, it is necessary to convert numerous observed point rainfall depths to provide an average rainfall depth over a certain area (Wilson, 1990). All the various methods proposed for the averaging of point rainfall depths over an area were considered in this study. However, Gericke and Du Plessis (2011) confirmed that there is a high degree of association (r^2 values > 0.9) between the various averaging methods when applied to the MRRC, with percentage differences < 17%. The latter results actually confirmed the even spatial distribution of the rainfall stations and the relatively flat topography of the MRRC (Gericke & Du Plessis, 2011). Based on these findings and in conjunction with the large amount of data and computations required, the Thiessen polygon method was selected as the most suitable method to use. The weighting procedure as applicable to the Thiessen polygon method [Eq. (1)] defines the zone of influence of each rainfall station by drawing lines between pairs of stations, bisecting the lines with perpendiculars. The total area enclosed within the polygon formed by these intersecting perpendiculars has rainfall of the same amount as the enclosed rainfall station (Wilson, 1990).

$$\overline{P} = \sum \frac{A_S P_i}{A_T} \tag{1}$$

where $\overline{P}$ is average rainfall depth (mm), A_S is area of the polygon surrounding a particular rainfall station (km^2), A_T is total catchment area (km^2), and P_i is point rainfall depth at a particular rainfall station (mm).

In essence, the Thiessen polygon method was used in each sub-catchment to convert the individual point rainfall hyetographs into an average catchment rainfall hyetograph using the *Create Thiessen Polygons* tool in the *Proximity* toolset contained in the *Analysis Tools* toolbox of ArcGIS™. The boundary of the resultant Thiessen polygons was selected in each case by the applicable sub-catchment boundary (polygon feature class). Thereafter, the areas of the polygons surrounding the stations within each sub-catchment was exported and converted to a Thiessen weight using the total sub-catchment area. The Thiessen weights were then utilised to approximate each rainfall station's contribution to the daily point rainfall within each sub-catchment.

3.2 Establishment of streamflow database

A streamflow database was established by evaluating, preparing and extracting primary flow data from the DWS flow database for the 16 continuous flow-gauging stations present in the MRRC. The average data record length of all the flow-gauging stations is 46 years (Gericke & Smithers, 2018). The screening criteria used to select the stations for the analyses include the following:

(a) **Stations common to previous flood studies:** Sixteen continuous flow-gauging stations used by Gericke and Smithers (2018) present in the MRRC were considered.
(b) **Record length:** Only streamflow records longer than 10 years were considered; as a result, one of the 16 flow-gauging stations did not meet the criteria. However, this flow-gauging station met the criteria as stipulated in (a) and (c); hence it was included in the analysis. This also ensured that a consistent approach is followed when the event-specific and average time parameter proportionality ratios are estimated at a sub-catchment level.
(c) **Catchment area:** In addition to above-listed criteria, the catchment areas of the selected flow-gauging stations should cover the range of sub-catchment areas present in the MRRC.

3.2.1 Extraction of flood hydrograph data

The next stage involved the identification and extraction of complete flood hydrographs from the primary flow data sets. The Flood Hydrograph Extraction Software (EX-HYD) developed by Görgens *et al.* (2007) was used to assist in identifying and extracting complete flood hydrographs. Complete flood hydrographs were extracted using the following selection criteria as proposed by Gericke and Smithers (2017; 2018):

(a) **Truncation levels:** Only flood events larger than the smallest annual maximum flood event on record were extracted. Consequently, all minor events were excluded, while all the flood events retained were characterised as multiple events being selected in a specific hydrological year. This approach resulted in a partial duration series (PDS) of independent flood peaks above a certain level.
(b) **Start/end time of flood hydrographs:** Flood peaks and flood volumes for the same event were obtained by extracting complete hydrographs. Initially, a large number of streamflow data points prior the start of a hydrograph, identified by physical inspection where the flow changes from nearly constant or declining values to rapidly increasing values, were included in order to identify the potential start of direct runoff. Thereafter, it was acknowledged that, by definition, the volume of effective rainfall is equal to the volume of direct runoff. Therefore, when separating a hydrograph into direct runoff and baseflow using a recursive filtering method, the separation point could be regarded as the start of direct runoff which coincides with the start of effective rainfall.
(c) **Extrapolation of rising and recession limbs to zero baseflow line:** In some cases, due to the nature of the data, the above-mentioned starting point identified by physical inspection as the lowest recording, did not necessarily coincide with the baseflow starting point as identified using the recursive filtering techniques. In such cases, a similar approach as followed by Görgens *et al.* (2007) was adopted, where a straight vertical line extrapolation from the identified starting point to the zero baseflow line was applied to enable the estimation of direct runoff volumes.

3.3 Development of Automated Toolkit

One of the specific objectives of this study is to develop a toolkit in the Microsoft Excel environment to automate the procedures of estimating the temporal characteristics of hyetograph-hydrograph responses. The Automated Toolkit consists of a collection of functions required to estimate the temporal characteristics from rainfall and streamflow records, including: (i) baseflow separation, (ii) time variable identification and estimation, (iii) time parameter estimation and, (iv) the estimation of time parameter proportionality ratios. Typically, the following modules are available in the Automated Toolkit:

(a) General catchment information;
(b) Processing of observed daily rainfall data;
(c) Extracted streamflow data;
(d) Analyses and plotting of hyetograph-hydrograph relationships; and
(e) Exporting of individual hyetograph-hydrograph pairs and summary of results.

The function for baseflow separation is based on the Hydrograph Analysis Tool (HAT) developed by Gericke (2016), while the remaining functions are proposed as a mechanism to extract compounded catchment hyetographs from multiple rainfall stations with mutual or synchronised events of recorded rainfall. The EX-HYD software developed by Görgens *et al.* (2007) was used to assist in identifying and extracting the complete flood hydrographs (*cf.* Section 3.2.1); hence, this function was not included in the toolkit. The Automated Toolkit attempts to mimic the typical convolution procedure practitioners would follow to visually inspect and interpret hyetograph-hydrograph data sets.

3.4 Analyses of hyetographs

In order to analyse rainfall hyetographs, the associated runoff events (as discussed in Section 3.2.1) need to be identified first. Consequently, a Visual Basic search algorithm was employed to identify the causal rainfall event in a window spanning *n* days before the start of the identified runoff event to the time of the last streamflow recording, where *n* is a user-defined parameter. For example, if *n* is set as 12 days, all rainfall records located in the window 12 days before the start of the runoff event to the last streamflow recording will be identified. The rainfall event starts at the first zero rainfall record in the search window and ends at the last zero recording. Subsequently, after the averaging of observed rainfall data per rainfall station and the synchronisation of mutual time interval rainfall-runoff events, the daily spatial distribution of any rainfall event could be estimated using Equation (2):

$$S_d = \left(\frac{\sum A_T TW_i}{A_T} \right) 100 \tag{2}$$

where S_d is daily spatial distribution (%), A_T is total catchment area (km^2), and TW_i is the Thiessen weight of each rainfall station that contributed to the daily rainfall.

During a rainfall event, not all the rainfall contributes to direct runoff. Initial abstractions, *e.g.* evaporation, transpiration, depression, detention, infiltration and interception by vegetation, reduce the effective runoff producing rainfall that a catchment receives. The Phi-index method [Eq. (3)] was used to yield an effective rainfall hyetograph.

$$I = \frac{P_T - Q_D}{t} \tag{3}$$

where I is Phi-index (mm/h), P_T is total rainfall (mm), Q_D is direct runoff, which equals the effective rainfall (mm), and t is the time period during which effective rainfall occurred (h).

Hence, Equation (3) enabled the plotting of possible hyetograph-hydrograph combinations to ultimately translate the effective runoff producing rainfall into direct runoff using a simplified convolution process as shown in Figure 4. The selection of an appropriate hyetograph-hydrograph event is characterised by the effective rainfall being equal to the direct runoff (as obtained from the baseflow separation applied to the hydrographs in Section 3.5). In cases where the effective rainfall and direct runoff volumes are not in equilibrium, an alternative rainfall period is selected and the process is repeated until equilibrium is reached. In each case, the event spatial distribution [Eq. (4)] is also automatically estimated for each rainfall period.

$$S_e = \left[\sum \left(\frac{P_i}{\sum_{i=0}^{r-1} P_i} \times S_{di} \right) \right] 100 \tag{4}$$

where S_e is event spatial distribution (%), i is number of frequency, P_i is weighted daily rainfall (mm), $\sum_{i=0}^{r-1} P_i$ is cumulative frequency of weighted daily rainfall (mm), r is range of frequency, and S_{di} is the daily spatial distribution (%).

The application of Equation (4) and matching of rainfall-runoff events with corresponding effective rainfall and direct runoff volumes are discussed in the next section. However, it is important to note that the identification and estimation of time variables *e.g.* start of effective rainfall (t_{er0}), centroid of effective rainfall (t_{erc}), end of effective rainfall (t_{ere}), and time of maximum rainfall (t_{rmax}) for each rainfall-runoff event, are already possible at this stage.

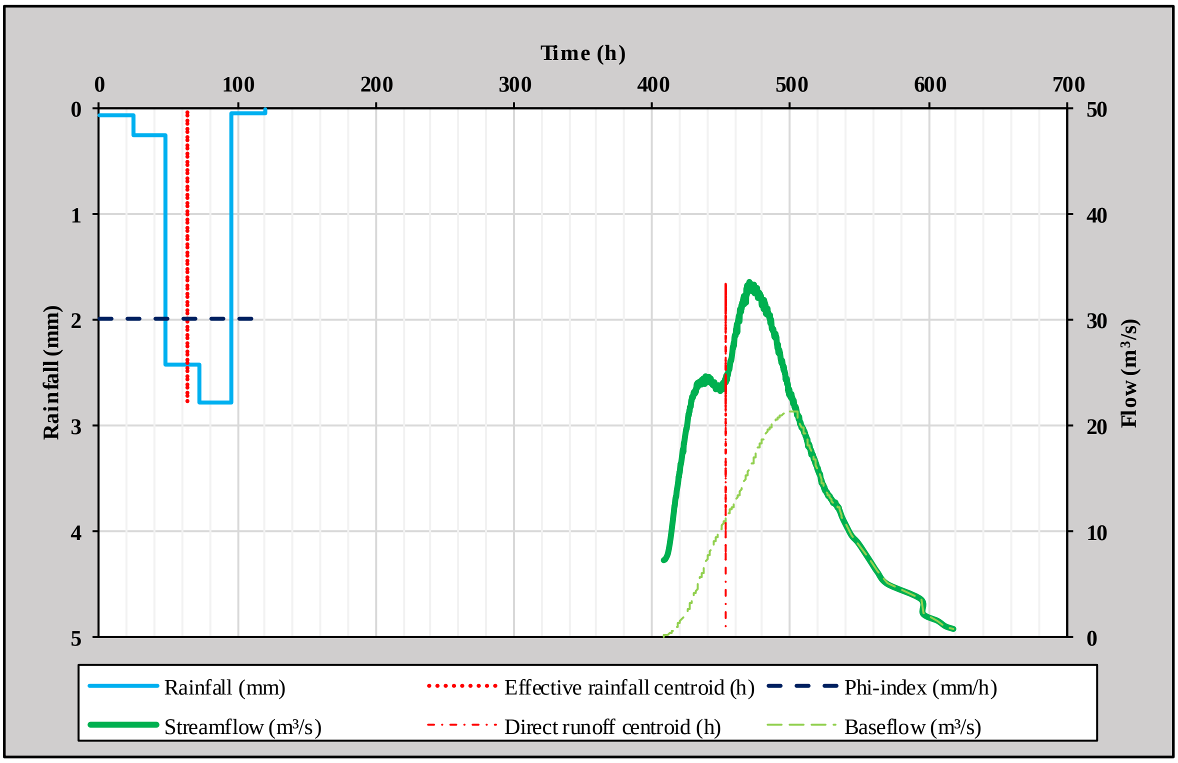

FIGURE 4: Example of a simplified convolution process with a compounded catchment hyetograph and resulting hydrograph

3.5 Analysis of hydrographs

The convolution process required to assess the time parameters, *e.g.* T_C, T_L and T_P, was based on the temporal relationship between an average compounded catchment hyetograph and a corresponding hydrograph in each sub-catchment. Conceptually, the proposed procedure is based on the definition that the volume of effective rainfall equals the volume of direct runoff when a hydrograph is separated into direct runoff and baseflow. The separation point on the hydrograph is also regarded as the start of direct runoff which coincides with the start of effective rainfall.

A number of methods, *e.g.* graphical, recursive digital filters, frequency-duration, and recession analysis have been proposed in the literature to separate direct runoff and baseflow (Arnold *et al.*, 1995; McCuen, 2005; Nathan & McMahon, 1990; Smakhtin, 2001). According to Smakhtin (2001), the most well-known and widely used recursive filtering methods are those developed by Nathan and McMahon (1990) and Chapman (1999). Smakhtin and Watkins (1997) also adopted the methodology as proposed by Nathan and McMahon (1990) with some modifications in a national-scale study in South Africa. Smakhtin and Watkins (1997) established that a fixed α-parameter value of 0.995 is suitable for most catchments in South Africa, although in some catchments, α-parameter values of 0.997 proved to be more appropriate. Hughes *et al.* (2003) also highlighted that a fixed β-parameter value of 0.5 could be used with daily time-step data, since there is more than enough flexibility in the setting of the α-parameter value to achieve an acceptable result. Consequently, a fixed α-parameter value = 0.995 and β-parameter value = 0.5 were used in this study.

Hence, based on these recommendations, as well as the need for consistency and reproducibility, Equation (5) as proposed by Nathan and McMahon (1990) and adopted by Smakhtin and Watkins (1997), was used in this study. Figure 4 (*cf.* Section 3.4) is also illustrative of a typical baseflow separation.

$$Q_{Dxi} = \alpha Q_{Dx(i-1)} + \beta(1+\alpha)(Q_{Txi} - Q_{Tx(i-1)}) \qquad (5)$$

where Q_{Dxi} is filtered direct runoff at time step i, which is subject to $Q_{Dxi} \geq 0$ for time i (m^3/s), α, β is filter parameters, and Q_{Txi} is the total streamflow (*i.e.* direct runoff plus baseflow) at time step i (m^3/s).

As discussed in Section 3.4, the volumes of effective rainfall and direct runoff need to be in equilibrium when a causal rainfall event of appropriate duration prior to the resulting runoff event is selected. This was done by matching the direct runoff depth (Q_D) with the effective rainfall depth (P_E) in Equation (6).

$$P_E = \frac{\sum \left(\frac{Q_{Dxi} + Q_{Dx(i-1)}}{2} \times \Delta T_{xi} \right)}{1000 A_T S_e} \quad (6)$$

where P_E is effective rainfall (mm), A_T is total catchment area (km^2), Q_{Dxi} is filtered direct runoff at time step i, which is subject to $Q_{Dxi} \geq 0$ for time i (m^3/s), S_e is event spatial distribution (%), and ΔT_{xi} is the absolute change in time at time step i (sec).

As a result, time variables *e.g.* start of total runoff (t_{q0}), time of peak discharge (t_{qpk}), centroid of direct runoff (t_{qc}), and time of the inflection point on the recession limb (t_{ip}) could be identified and estimated for each rainfall-runoff event at a sub-catchment level.

3.6 Estimation of time parameters and proportionality ratios

Table 1 provides a summary of the different time, Time Parameter (TP) equations and Time Parameter Proportionality Ratio (TPPR) estimation procedures included in the Automated Toolkit.

TABLE 1: Summative description of TP equations and TPPR estimation procedures included in the Automated Toolkit. The letter in brackets () is used as cross-reference to the time parameter definitions (a) to (d) as defined and described in Section 1.2 (*cf.* Figure 1)

Symbol	Equation	Description
T_C (a)	t_{ip} - t_{ere}	Time of concentration definition (a)
T_C (b) & T_L (a/b)	t_{qpk} - t_{erc}	Time of concentration definition (b) and lag time definition (a/b)
T_C (c)	t_{qpk} - t_{rmax}	Time of concentration definition (c)
T_L (c)	t_{qc} - t_{erc}	Lag time definition (c)
T_C (d)	t_{qpk} - t_{q0}	Time of concentration definition (d)
TPPR 1	$\frac{T_C(a)}{T_L(a\,or\,b)}$	Time Parameter Proportionality Ratio (1)
TPPR 2	$\frac{T_C(b)}{T_L(a\,or\,b)}$	Time Parameter Proportionality Ratio (2)
TPPR 3	$\frac{T_C(c)}{T_L(a\,or\,b)}$	Time Parameter Proportionality Ratio (3)
TPPR 4	$\frac{T_C(d)}{T_L(a\,or\,b)}$	Time Parameter Proportionality Ratio (4)
TPPR 5	$\frac{T_C(a)}{T_L(c)}$	Time Parameter Proportionality Ratio (5)
TPPR 6	$\frac{T_C(b)}{T_L(c)}$	Time Parameter Proportionality Ratio (6)
TPPR 7	$\frac{T_C(c)}{T_L(c)}$	Time Parameter Proportionality Ratio (7)
TPPR 8	$\frac{T_C(d)}{T_L(c)}$	Time Parameter Proportionality Ratio (8)

4 RESULTS AND DICUSSION

4.1 Hyetograph-hydrograph analyses

The average period of record for observed rainfall data ranged from 1901 to 2001 in each of the 16 sub-catchments of the MRRC. Sub-catchments C5H022 and C5H023 could not be analysed, since the rainfall data was insufficient to match the complete flood hydrographs identified and extracted for the specific periods under consideration. A total of 1 134 complete flood hydrographs or runoff events were extracted from the primary flow data sets, with between 13 and 117 individual flood hydrographs per flow-gauging station/sub-catchment.

A total of 394 hyetograph-hydrograph data sets representative of specific rainfall-runoff events were extracted and analysed using the Automated Toolkit. A number of runoff events could not be analysed due to a lack of rainfall data after the year 2001. Hence, this resulted in a shortfall; however, a number of runoff events could also not be analysed due to the difficulty experienced to identify the inflection point on a hydrograph recession limb or due to multi-peaked hydrographs. In essence, only 35% of the extracted runoff events could be analysed, *i.e.* 394 rainfall-runoff events.

4.2 Estimation of time parameters

In considering the analyses of the 394 hyetograph-hydrograph events, it was quite evident that the seven different time parameter definitions contribute to the time parameter variability, which is also influenced by the event spatial distribution (S_e), the variation in peak discharge (Q_P) and the distance (L) between the rainfall station (where the maximum rainfall depth was recorded) and the sub-catchment outlet. In general, the largest Q_P and direct runoff (Q_D) values are associated with the likelihood of the entire sub-catchment receiving rainfall of a high intensity for the critical storm duration, which in principal, represents the conceptual T_C.

Shorter response times, *i.e.* lower T_C, T_L and T_P values could be expected to occur when the effective rainfall does not cover the entire catchment, especially when a rainfall event is centred near the outlet of a sub-catchment. In considering the average time parameters illustrated in Figure 5 to Figure 7 for each sub-catchment, it is evident that these average time parameters are in agreement with the preliminary findings of Gericke and Smithers (2017; 2018), *i.e.* $T_P \approx T_C \approx T_L$ at a medium to large catchment level.

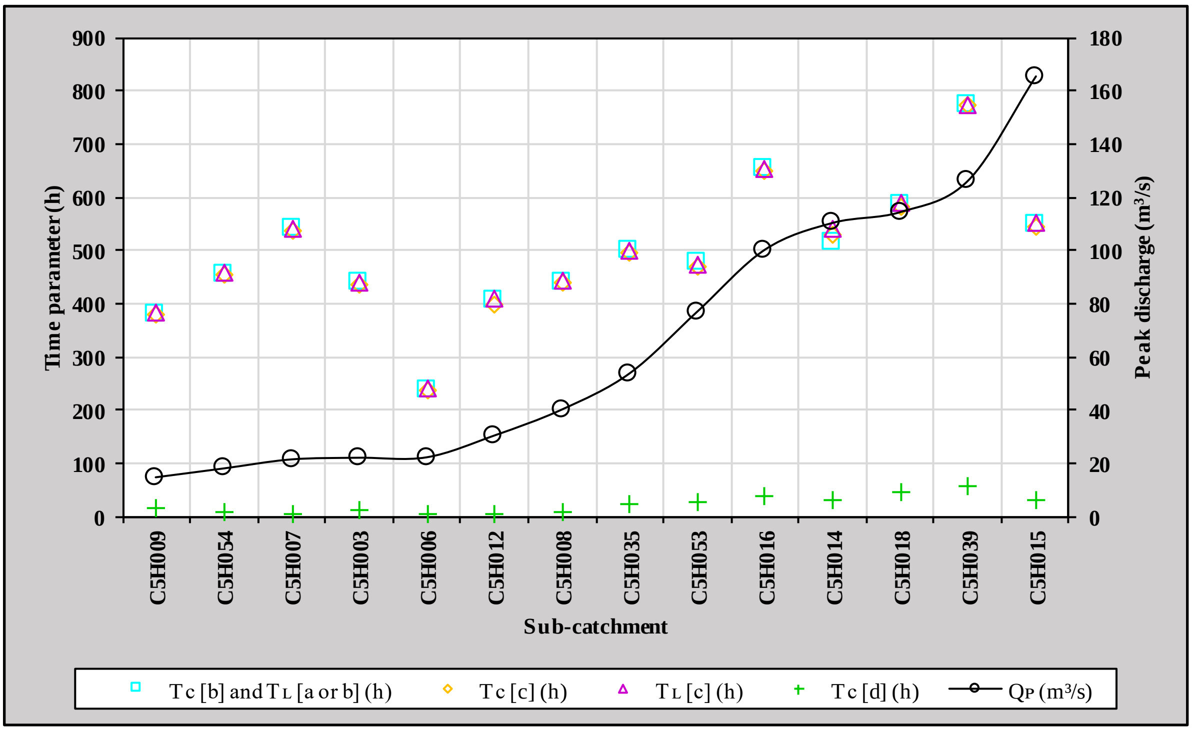

FIGURE 5: Summary of the association between average time parameters (based on different definitions) and the average peak discharge (Q_P) of all rainfall events at a sub-catchment level in the MRRC

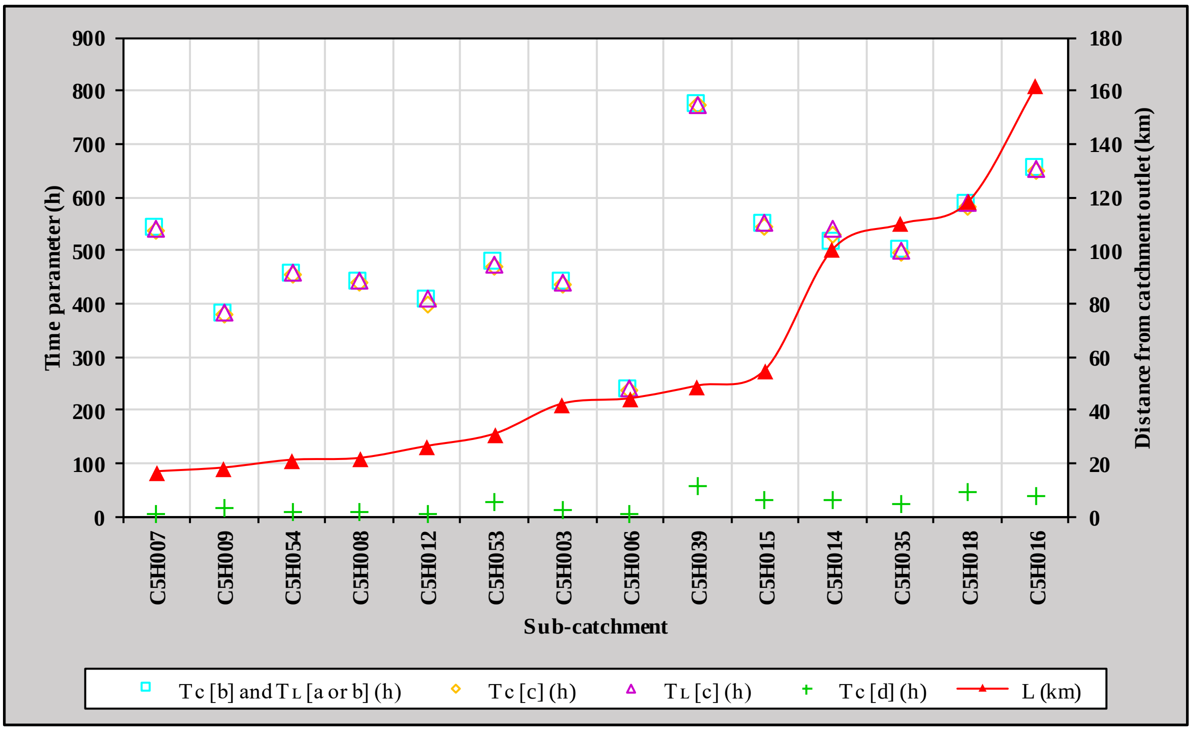

FIGURE 6: Summary of the association between average time parameters (based on different definitions) and the average distance (*L*) of all rainfall events from the catchment outlet at a sub-catchment level in the MRRC

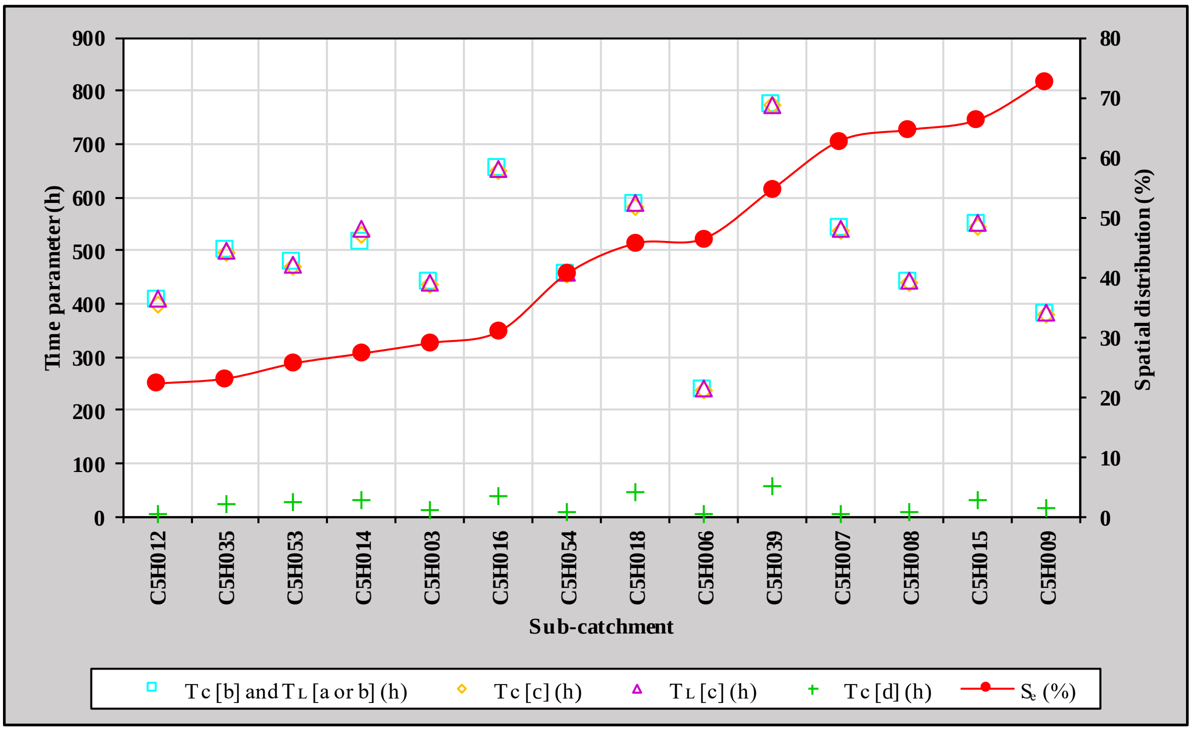

FIGURE 7: Summary of the association between average time parameters (based on different definitions) and the average spatial distribution of all rainfall events (S_e) at a sub-catchment level in the MRRC

Figure 5 shows a clear association between average time parameters and the average Q_P of all rainfall events at a sub-catchment level in the MRRC. In other words, on average, high time parameter values are typically associated with high peak discharge values. However, Figure 6 does not show a clear association between average time parameters and the average L of all rainfall events from the catchment outlet. Figure 7 also shows no apparent association between average time parameters and the average S_e of all rainfall events. The information presented in Figure 5 to Figure 7 also shows the insignificance of T_C (d) when compared to the other T_C definitions. The latter difference could be ascribed to the fact that this definition is also used to define the time to peak for any specific rainfall event, and/or could also be ascribed to the runoff events being wrongfully regarded as baseflow instead of being part of the rising limb of the hydrograph, *i.e.* direct runoff.

4.3 Estimation of time parameter proportionality rations

In considering the T_C, T_L and T_P pair values obtained from the 394 hyetograph-hydrograph events, a relatively low variability is evident between the different time parameter proportionality ratios (TPPR 1 to TPPR 8) at a sub-catchment level. In general, where T_L is defined as the time from the centroid of effective rainfall to the peak discharge (McCuen, 2009), T_C and T_L are related by $T_C = 1.003T_L$ (TPPR 1 to TPPR 3, as illustrated in Figure 8). In using T_L defined as the time from the centroid of effective rainfall to the centroid of direct runoff (McCuen, 2009), the proportionality ratio reduced to 0.992 (TPPR 5 to TPPR 7, as illustrated in Figure 8).

The average time parameter proportionality ratios, in the MRRC, presented in Figure 8 showed no clear association with the average S_e, average Q_P and average L (distance between the rainfall station where the maximum rainfall depth was recorded and the sub-catchment outlet) values, thus this data was not included. However, the average time parameter proportionality ratios highlighted the insignificance of TPPR 4 and TPPR 8. This is due to the fact that T_C definition (d) is also one of the definitions used to quantify T_P and in general the average values of T_C definition (d) were ± 21 times smaller compared to the other average T_C definition values. In considering the average time parameter proportionality ratios illustrated in Figure 8 for each sub-catchment, the average time parameter proportionality ratios confirm the preliminary findings of Gericke and Smithers (2017; 2018), *i.e.* $T_P \approx T_C \approx T_L$ at a medium to large catchment level.

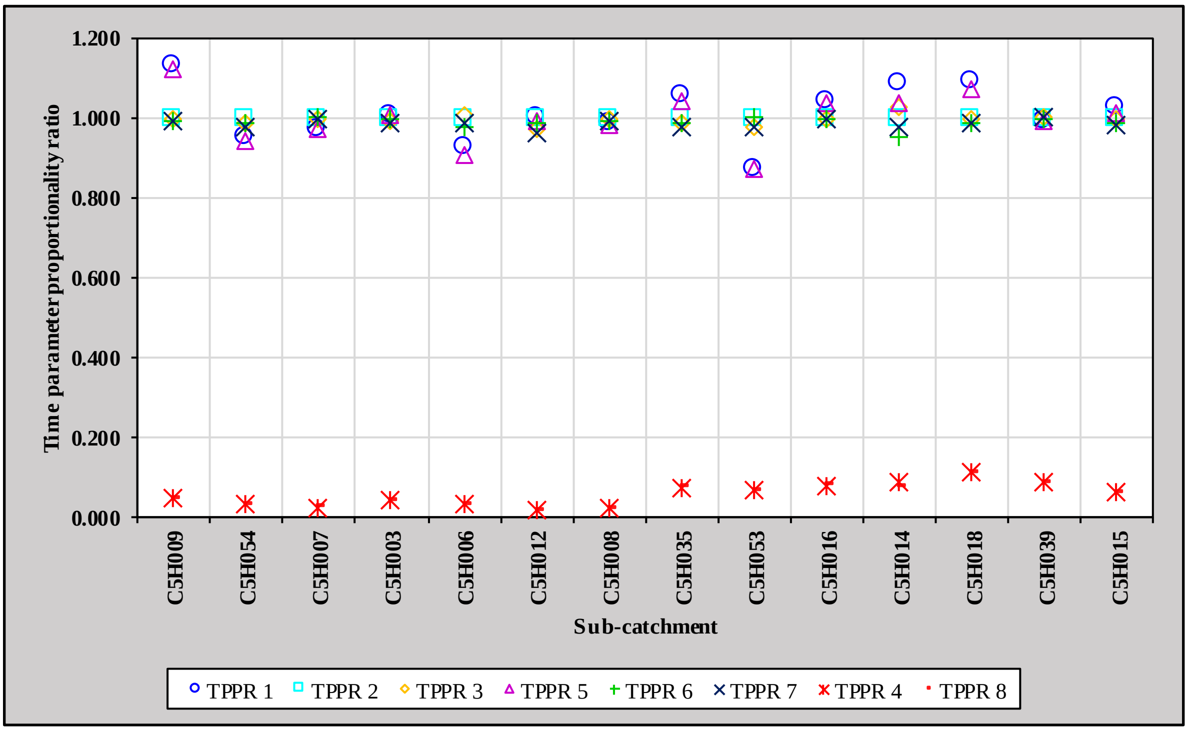

FIGURE 8: Summary of the average time parameter proportionality ratios at a sub-catchment level in the MRRC

5 CONCLUSION

The estimation of time parameters and time parameter proportionality ratios in large sub-catchments of the MRRC was the objective of this study. An enhanced methodology was developed to estimate catchment response time parameters and time parameter proportionality ratios at a large catchment level in the MRRC, while considering the spatial distribution of storm events and the distance thereof from the catchment outlet. The major findings are as follows:

(a) Time parameter estimates based on the seven different theoretical time parameter definitions proved to be highly variable due to the spatial and temporal distribution of rainfall events, variation in peak discharges and the distance of the rainfall events from the catchment outlet.

(b) Time parameter proportionality ratios are characterised by a relatively low variability at a larger catchment level in the MRRC.

(c) In this study, where T_L is defined as the time from the centroid of effective rainfall to the peak discharge of direct runoff, T_C and T_L are related by $T_C = 1.003T_L$ and where T_L is defined as the time from the centroid of effective rainfall to the centroid of direct runoff, the proportionality ratio reduces to 0.992.

(d) In all the sub-catchments under consideration, the preliminary findings of Gericke and Smithers (2017; 2018), *i.e.* $T_P \approx T_C \approx T_L$, were confirmed. In other words, it highlighted that the proportionality ratios currently proposed for small catchments, *i.e.* $T_C = 1.417T_L$ and $T_C = 1.667T_L$, are not applicable at larger catchment levels.

Building upon the critical assessment of the available time parameter definitions and proportionality ratios, it is envisaged that the implementation and expansion of both the identified research values and adopted methodology to other catchments in South Africa and internationally, will ultimately contribute towards improved time parameter estimations at a catchment level. Consequently, the improved time parameter estimations will also result in improved design flood estimations.

6 ACKNOWLEDGEMENTS

Support for this research by the National Research Foundation (NRF) and Central University of Technology, Free State (CUT) is gratefully acknowledged. We also wish to thank the anonymous reviewers for their constructive review comments, which have helped to significantly improve the paper.

7 ORCID

C.E. Allnutt[1, 2] https://orcid.org/0000-0002-9700-159X
O.J. Gericke[3] https://orcid.org/0000-0003-0371-2516
J.P.J. Pietersen[4] https://orcid.org/0000-0001-5254-5684

8 REFERENCES

Arnold, J. G., Allen, P. M., Muttiah, R. & Bernhardt, G. (1995). Automated base flow separation and recession analysis techniques. *Ground Water, 33*(6), 1010–1018.

Bell, F. C. & Kar, S. O. (1969). Characteristic response times in design flood estimation. *Journal of Hydrology, 8*, 173–196.

Chapman, T. (1999). A comparison of algorithms for streamflow recession and baseflow separation. *Hydrological Processes, 13*, 701–714.

Chow, V. T., Maidment, D. R. & Mays, L. W. (1988). *Applied Hydrology*. New York, USA: McGraw-Hill.

Clark, C. O. (1945). Storage and the unit hydrograph. *Transactions, American Society of Civil Engineers, 110*, 1419–1446.

CSIR (2001). *GIS Data: Classified Raster Data for National Coverage based on 31 Land Cover Types*. Pretoria, RSA: Council for Scientific and Industrial Research, Environmentek.

Dingman, S. L. (2002). *Physical Hydrology*. New York, USA: Macmillan.

Dow, C. L. (2007). Assessing regional land-use/cover influence on New Jersey Pinelands streamflow through hydrograph analysis. *Hydrological Processes, 21*, 185–197.

DWAF (1995). GIS Data: Drainage Regions of South Africa. Pretoria, RSA: Department of Water Affairs and Forestry.

Elsenbeer, H. & Vertessy, R. A. (2000). Stormflow generation and flow path characteristics in an Amazonian rainforest catchment. *Hydrological Processes, 14*, 2367–2381.

Fang, X., Thompson, D. B., Cleveland, T. G., Pradhan, P. & Malla, R. (2008). Time of concentration estimated using watershed parameters by automated and manual methods. *Journal of Irrigation and Drainage Engineering, 134*(2), 202–211.

Ferguson, B. K. & Suckling, P. W. (1990). Changing rainfall-runoff relationships in the urbanizing Peachtree Creek Watershed. *Water Resources Bulletin, 26*(2), 313–322.

Folmar, N. D. & Miller, A. C. (2008). Development of an empirical lag time equation. *Journal of Irrigation and Drainage Engineering, 134*(4), 501–506.

Gericke, O. J. (2016). *Estimation of Catchment Response Time in Medium to Large Catchments in South Africa.* PhD Eng. Unpublished doctoral thesis, University of KwaZulu-Natal.

Gericke, O. J. & Du Plessis, J. A. (2011). Evaluation of critical storm duration rainfall estimates used in flood hydrology in South Africa. *Water SA, 37*(4), 453–470.

Gericke, O. J. & Smithers, J. C. (2014). Review of methods used to estimate catchment response time for the purpose of peak discharge estimation. *Hydrological Sciences Journal, 59*(11), 1935–1971.

Gericke, O. J. & Smithers, J. C. (2017). Direct estimation of catchment response time parameters in medium to large catchments using observed streamflow data. *Hydrological Processes, 31*(5), 1125–1143.

Gericke, O. J. & Smithers, J. C. (2018). An improved and consistent approach to estimate catchment response time: Case study in the C5 drainage region, South Africa. *Journal of Flood Risk Management, 11*(2018), S284–S301.

Görgens, A. H. M., Lyons, S., Hayes, L., Makhabane, M. & Maluleke, D. (2007). *Modernised South African Design Flood Practice in the Context of Dam Safety*. WRC Report No. 1420/2/07, Pretoria, RSA: Water Research Commission.

Heggen, R. (2003). Time of concentration, lag time and time to peak. *In:* Shrestha, B. & Rajbhandari, R. (eds.) *Proceedings of Regional Training Course: Application of Geo-informatics for Water Resources Management*. Kathmandu, Nepal: International Centre for Integrated Mountain Development.

Holton, H. N. & Overton, D. E. (1963). Analysis and application of simple hydrographs. *Journal of Hydrology, 1*, 250–264.

Hood, M. J., Clausen, J. C. & Warner, G. S. (2007). Comparison of stormwater lag times for low impact and traditional residential development. *Journal of the American Water Resources Association, 43*(4), 1036–1046.

Hughes, D. A., Hannart, P. & Watkins, D. (2003). Continuous baseflow from time series of daily and monthly streamflow data. *Water SA, 29*(1), 43–48.

Jena, S. K. & Tiwari, K. N. (2006). Modelling synthetic unit hydrograph parameters with geomorphologic parameters of watersheds. *Journal of Hydrology, 319*, 1–14.

Johnstone, D. & Cross, W. P. (1949). *Elements of Applied Hydrology*. New York, USA: Ronald Press.

Jones, J. A. & Grant, G. E. (1996). Peak flow response to clear-cutting and roads in small and large basins. *Water Resource Research, 32*(4), 959–947.

Kerby, W. S. (1959). Time of concentration for overland flow. *Civil Engineering, 29*(3), 174.

Kirpich, Z. P. (1940). Time of concentration of small agricultural watersheds. *Civil Engineering, 10*(6), 362.

Lim, K. J., Engel, B. A., Tang, Z., Choi, J., Kim, K., Muthukrishnan, S. & Tripathy, D. (2005). Automated Web GIS Based Hydrograph Analysis Tool, WHAT. *Journal of the American Water Resource Association, 41*(6), 1407–1416.

Linsley, R. K., Kohler, M. A. & Paulhus, J. L. H. (1988). *Hydrology for Engineers*. Singapore: McGraw-Hill.

Lynch, S. D. (2004). *Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*. WRC Report No. 1156/1/04, Pretoria, RSA: Water Research Commission.

McCuen, R. H. (2005). *Hydrologic Analysis and Design.* Upper Saddle River, New York, USA: Prentice-Hall.

McCuen, R. H. (2009). Uncertainty analyses of watershed time parameters. *Journal of Hydrologic Engineering, 14*(5), 490–498.

McCuen, R. H., Wong, S. L. & Rawls, W. J. (1984). Estimating urban time of concentration. *Journal of Hydraulic Engineering, 110*(7), 887–904.

Midgley, D. C., Pitman, W. V. & Middleton, B. J. (1994). *Surface Water Resources of South Africa, Volume 2, Drainage Region C, Vaal: Appendices*. WRC Report 298/2.1/94, Pretoria, RSA: Water Research Commission.

Mimikou, M. (1984). Regional relationships between basin size and runoff characteristics. *Hydrological Sciences Journal, 29*(1, 3), 63–73.

Mockus, V. (1957). *Use of Storm and Watershed Characteristics in Synthetic Hydrograph Analysis and Application.* Washington, DC, USA: United States Department of Agriculture, Soil Conservation Service.

Nathan, R. J. & McMahon, T. A. (1990). Evaluation of automated techniques for baseflow and recession analyses. *Water Resources Research, 26*(7), 1465–1473.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. (2005). *Soil and Water Assessment Tool: Theoretical Documentation.* Temple, Texas, USA: Agricultural Research Service and Blackland Research Center.

Pavlovic, S. B. & Moglen, G. E. (2008). Discretization issues in travel time calculations. *Journal of Hydrologic Engineering, 13*(2), 71–79.

Pietersen, J. P. J. (2016). *Areal Reduction Factors for Design Rainfall Estimation in the C5 Secondary Drainage Region of South Africa.* M Tech Eng. Unpublished masters dissertation, Central University of Technology, Free State.

Piggott, A. R., Moin, S. & Southam, C. (2005). A revised approach to the UKIH method for the calculation of baseflow. *Hydrological Sciences Journal, 50*, 911–920.

Potter, K. W. & Faulkner, E. B. (1987). Catchment response time as predicator of flood quantiles. *Water Resources Bulletin, 25*(5), 857–861.

Pullen, R. A. (1969). *Synthetic Unit Graphs for South Africa*. HRU Report No. 3/69, Johannesburg, RSA: University of the Witwatersrand.

Ramser, C. E. (1927). Runoff from small agricultural areas. *Journal of Agricultural Engineering, 34*(9), 797–823.

Rutledge, A. T. (1998). *Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow data*. Report No. 984148: 43, USA: United States Geological Survey Water Resources Investigations.

Sabol, G. V. (2008). *Hydrologic Basin Response Parameter Estimation Guidelines*. Dam Safety Report, State of Colorado, Scottsdale, AZ, USA: Tierra Grande International Incorporated.

SANRAL (2013). *Drainage Manual.* Pretoria, RSA: South African National Roads Agency Limited.

Schmidt, E. J. & Schulze, R. E. (1984). *Improved Estimation of Peak Flow Rates using Modified SCS Lag Equations*. ACRU Report No. 17, Pietermaritzburg, RSA: University of Natal.

Schultz, G. A. (1964). *Studies in Flood Hydrograph Synthetisation.* MSc. Unpublished masters dissertation, University of the Witwatersrand.

Seybert, T. A. (2006). *Stormwater Management for Land Development: Methods and Calculations for Quantity Control.* Hoboken, New Jersey, USA: John Wiley and Sons Incorporated.

Simas, M. J. C. (1996). *Lag Time Characteristics in Small Watersheds in the United States.* PhD. Unpublished doctoral thesis, University of Arizona.

Sloto, R. A. & Crouse, M. Y. (1996). *HYSEP: A computer program for streamflow hydrograph analysis*. Report No. 90–4040: 46, USA: United States Geological Survey Water Resources Investigations.

Smakhtin, V. U. (2001). Low flow hydrology: A review. *Journal of Hydrology, 240*(2001), 147–186.

Smakhtin, V. U. & Watkins, D. A. (1997). *Low Flow Estimation in South Africa.* WRC Report No. 494/1/97, Pretoria, RSA: Water Research Commission.

Smithers, J. C., Chetty, K. T., Frezghi, M. S., Knoesen, D. M. & Tewolde, M. H. (2013). Development and assessment of a daily time step continuous simulation modelling approach for design flood estimation at ungauged locations: ACRU model and Thukela Catchment case study. *Water SA, 39*(4), 449–458.

Snyder, F. F. (1938). Synthetic unit hydrographs. *Transactions of American Geophysical Union, 19*, 447.

Sujono, J., Shikasho, S. & Hiramatsu, K. (2004). A comparison of techniques for hydrograph recession analysis. *Hydrological Processes, 18*, 403–413.

Thomas, W. O., Monde, M. C. & Davis, S. R. (2000). Estimation of time of concentration for Maryland streams. *Journal of the Transportation Research Board, 1720*, 95–99.

USACE (2001). *HEC-HMS Hydrologic Modelling System: User's Manual, Version 2.2.1.* Vicksburg, Mississippi, USA: United States Army Corps of Engineers.

USBR (1973). *Design of Small Dams.* Washington, DC, USA: United States Bureau of Reclamation, Water Resources Technical Publi cation.

USDA NRCS (2010). Time of concentration. *In:* Woodward, D. E., et al. (ed.) *National Engineering Handbook.* Washington, DC, USA: United States Department of Agriculture Natural Resources Conservati on Service.

USDA SCS (1985). Hydrology. *In:* Kent, K. M., et al. (ed.) *National Engineering Handbook.* Washington, DC, USA: United States Department of Agriculture Soil Conservation Service.

USGS. (2016). *EarthExplorer* [Online]. United States Geological Survey. Available: https://earthexplorer.usgs.gov/ [Accessed 19 September 2016].

Viessman, W., Lewis, G. L. & Knapp, J. W. (1989). *Introduction to Hydrology.* New York, USA: Harper and Row Publishers Incorporated.

Watt, W. E. & Chow, K. C. A. (1985). A general expression for basin lag time. *Canadian Journal of Civil Engineering, 12*, 294–300.

White, K. & Sloto, P. A. (1990). *Base flow frequency characteristics of selected Pennsylvanian streams*. Report No. 90-4160: 66, USA: United States Geological Survey Water Resources Investigations.

Wilson, E. M. (1990). *Engineering Hydrology.* London, UK: Macmillan Press Limited.

9 WORD COUNT

The paper has been summarised as far as possible. A further reduction of the text in the paper would leave the reader confused or unaware of the background of the study. Total word count excluding references, illustrations and tables: 6729.