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An improved and consistent approach to estimate catchment response time parameters: case study in the C5 drainage region, South Africa

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Base flow; direct run-off; lag time; time of concentration; time to peak.

Abstract

Large errors in estimates of peak discharge in medium to large catchments in South Africa can be largely ascribed to significant errors in the estimation of the catchment response time, mainly as a consequence of the use of inappropriate time variables, the inadequate use of a simplified convolution process between rainfall–run-off time variables, and the lack of locally developed empirical methods to estimate catchment response time parameters. Furthermore, the use of a typical convolution process between a single hyetograph and hydrograph to estimate observed time parameters at large catchment scales is regarded as not practical, as such simplification is not applicable in real, large heterogeneous catchments where antecedent moisture from previous rainfall events and spatially non-uniform rainfall hyetographs can result in multipeaked hydrographs. This paper presents the development and evaluation of an alternative, improved and consistent approach to estimate catchment response time expressed as the time to peak (T_P) in the C5 secondary drainage region in South Africa, while the interrelationship, similarity and proportionality ratios between T_P and the conceptual time of concentration (T_C) and lag time (T_L) are also investigated.

Introduction

Most hydrological analyses of rainfall and run-off to determine hazard or risk, especially in ungauged catchments, require the estimation of catchment response time parameters as primary input. In essence, time variables describe the individual events defined on either a hyetograph or hydrograph, while a time parameter is defined by the difference between two inter-related time variables (McCuen, 2005). The most frequently used catchment response time parameters are the time of concentration (T_C), lag time (T_L) and time to peak (T_P), which are normally defined in terms of the physical catchment characteristics and/or distribution of effective rainfall and direct run-off (USDA NRCS, 2010). Time parameters are estimated using either empirically or hydraulically based methods (McCuen *et al.*, 1984; McCuen, 2009), although analytical or semi-analytical methods are also sometimes used. In the empirical methods, the time parameters are related to the geomorphological and climatological parameters of a catchment using stepwise multiple regression analysis by taking both overland and main watercourse/channel flows into consideration (Kirpich, 1940; Watt and Chow, 1985; Papadakis and Kazan, 1987; Sabol, 1993). The hydraulically based T_C estimates are limited to the overland flow regime, which is best presented by either uniform flow theory or basic wave (dynamic and kinematic) mechanics (Heggen, 2003).

In South Africa (SA), unfortunately, none of the empirical T_C estimation methods recommended for general use was developed and verified using local data. In small, flat catchments with overland flow being dominant, the use of the Kerby equation (Kerby, 1959) is recommended, while the empirical US Bureau of Reclamation equation (USBR, 1973) is used 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 United States for catchment areas less than 4 ha and 45 ha, respectively (McCuen *et al.*, 1984). However, practitioners in SA commonly apply these ‘recommended methods’ outside their bounds, both in terms of areal extent and their original regions of development, without using any local correction factors. In addition to the application of the empirical time parameter estimation methods outside their bounds, practitioners frequently also apply some of the deterministic flood estimation methods, e.g. rational method, beyond their intended scale of application. Consequently, these practices might contribute to even larger errors in estimates of peak discharge.

The empirical estimates of T_L used in SA are limited to the family of equations developed by the Hydrological Research Unit (HRU; Pullen, 1969); the US Department of Agriculture Natural Resource Conservation Service (USDA NRCS), formerly known as the USDA Soil Conservation Service (USDA SCS, 1985) and SCS-SA (Schmidt and Schulze, 1984) equations. Both the HRU and Schmidt-Schulze T_L equations were locally developed and verified. The use of the HRU methodology is recommended for catchment areas less than 5000 km^2 and T_L is defined as the time lapse between the centroid of effective rainfall and the centroid of a unit hydrograph (Pullen, 1969). The Schmidt-Schulze (SCS-SA) methodology is limited to small catchments (up to 30 km^2) with T_L being defined as the time from the centroid of effective rainfall to the time of the peak discharge of total or direct run-off.

The estimation of T_C or T_L from observed hyetograph–hydrograph data, referred to as T_{Cx} and T_{Lx}, respectively in this paper, at a large catchment scale normally requires a convolution process based on the temporal relationship between averaged hyetographs from numerous rainfall stations to estimate catchment rainfall and the resulting hydrograph. Conceptually, such a procedure assumes that the volume of direct run-off is equal to the volume of effective rainfall, and that all rainfall prior to the start of direct run-off is initial abstraction, after which, the loss rate is assumed to be constant. However, this simplification ignores the 'memory effect' of previous rainfall events. The hyetographs from different gauges in the catchment require synchronisation between point rainfall data sets in order to estimate correctly the catchment hyetograph. These inherent procedural limitations, in addition to the difficulty in estimating catchment rainfall for large catchments due to the lack of continuously recorded rainfall data, as well as the problems encountered with the estimation of hyetographs and/or hydrographs at large catchment scales, emphasise the need for the development of an alternative approach (Gericke and Smithers, 2014).

Gericke and Smithers (2014) demonstrated that the approximation of $T_C \approx T_P$ could be used as basis for such an alternative approach at large catchment scales, while the use of this approximation could be justified by acknowledging that, by definition, the volume of effective rainfall is equal to the volume of direct run-off. Therefore, when separating a hydrograph into direct run-off and base flow, the separation point could be regarded as the start of direct run-off which coincides with the onset of effective rainfall. In using such an approach, the required extensive convolution process is eliminated, since T_{Px} is obtained directly from observed stream flow data without the need for rainfall data.

This paper provides preliminary insight into the development and evaluation of an alternative, improved and consistent approach to estimate representative catchment response time by investigating the interrelationship and similarity between these time parameters in the C5 secondary drainage region in SA. The objectives of the study reported in this paper are discussed in the next section, followed by an overview of the location and characteristics of the pilot study area. Thereafter, the methodologies involved in assessing the objectives are detailed, followed by the results, discussion, and conclusions.

Objectives and assumptions

The overall objective of this study is to improve estimates of peak discharge at a medium to large catchment scale (e.g. 50 km^2 to 35 000 km^2) in the C5 secondary drainage region in SA by developing an empirical equation to estimate the catchment response time, which has a significant influence on the resulting hydrograph shape and peak discharge. The focus is on using an alternative and consistent approach to estimate catchment response time, i.e. adopt the approximation of $T_C \approx T_P$ as recommended by Gericke and Smithers (2014) with T_{Px} estimated directly from the observed stream flow data. The specific objectives of this study are: (1) to extract the flood event characteristics (e.g. peak, volume and duration) using primary stream flow data from 16 flow-gauging stations located in the pilot study area, (2) to separate the extracted hydrographs into direct run-off and base flow using different recursive filtering methods, (3) to estimate the direct run-off/effective rainfall volumes, (4) to investigate and analyse the interrelationship between different hydrograph shape parameters (T_P, T_C, T_L) and key climatological and geomorphological catchment variables in order to verify the developed regionalised empirically based time parameter equation, and (5) to compare the observed time parameters with both the developed relationship and 'recommended methods' currently used in SA in order to highlight the impact of inconsistent results when translated into estimates of peak discharge.

It is important to note that this study will primarily highlight biases and inconsistencies in the 'recommended methods' currently used when compared to the calibrated regional time parameter equation and observed time parameters. However, when translating the time parameter estimation results into design peak discharges, the significance of the results are evident.

This study is based on the following assumptions:

1. **The conceptual T_C equals the time of virtual equilibrium (T_{VE}):** The conceptual T_C is defined as the time

required for run-off, as a result of effective rainfall with a uniform spatial and temporal distribution over a catchment, to contribute to the peak discharge at the catchment outlet, or, in other words, the time required for a 'water particle' to travel from the catchment boundary along the longest watercourse to the catchment outlet (Kirpich, 1940; McCuen *et al.*, 1984; McCuen, 2005; USDA NRCS, 2010; SANRAL, 2013). T_{VE} is the time when response equals 97% of the total surface run-off, which is also regarded as a practical measure of the actual equilibrium time (Larson, 1965). The actual equilibrium time is difficult to determine due to the gradual response rate to the input rate. Consequently, T_C defined according to the 'water particle' concept would be equivalent to T_{VE}. Gericke and Smithers (2014) also obtained results in close agreement with Larson's (1965) concept of virtual equilibrium, i.e. $T_{VE} \approx 0.97T_C$.

2. **The conceptual T_C equals T_P:** The T_P is normally defined as the time interval between the start of effective rainfall and the peak discharge of a single-peaked hydrograph, but this definition is also regarded as the conceptual definition of T_C (McCuen *et al.*, 1984; USDA SCS, 1985; Linsley *et al.*, 1988; Seybert, 2006). However, in medium to large catchments, T_{Px} could be defined as the duration of the total net rise of a multiple-peaked hydrograph (Du Plessis, 1984) as shown in Figure 1 and expressed in Eqn (1).

$$T_{Px} = t_1 + t_2 + t_3 + t_n \tag{1}$$

where T_{Px} = observed time to peak which equals the conceptual T_C (hours), and $t_{1,2,3,n}$ = duration of the total net rise (excluding the in-between recession limbs) of a multiple-peaked hydrograph if three or more discernible peaks are evident (hours).

3. **T_C-T_L proportionality ratio:** The catchment T_{Lx}, defined as the time from the centroid of effective rainfall to the time of the peak discharge of total or direct run-off (Figure 1), is related to the conceptual T_C by $T_{Lx} = 0.6T_C$ (McCuen, 2009).

In acknowledging the similarity between the definitions of the conceptual T_C, T_{VE} and T_P, Gericke and Smithers (2014) argued that the approximation of $T_C \approx T_P$ in medium to large catchments could be regarded as sufficiently accurate. However, it is expected that, T_{Px} derived from a number of flood events, will vary over a wide range of values. Thus, factors such as antecedent moisture conditions and non-uniformity in the temporal and spatial distribution of storm rainfall have to be accounted for when flood hydrographs are extracted from the observed stream flow data sets.

Study area

SA, which is located on the most southern tip of Africa (Figure 2), is demarcated into 22 primary drainage regions, which are further delineated into 148 secondary drainage

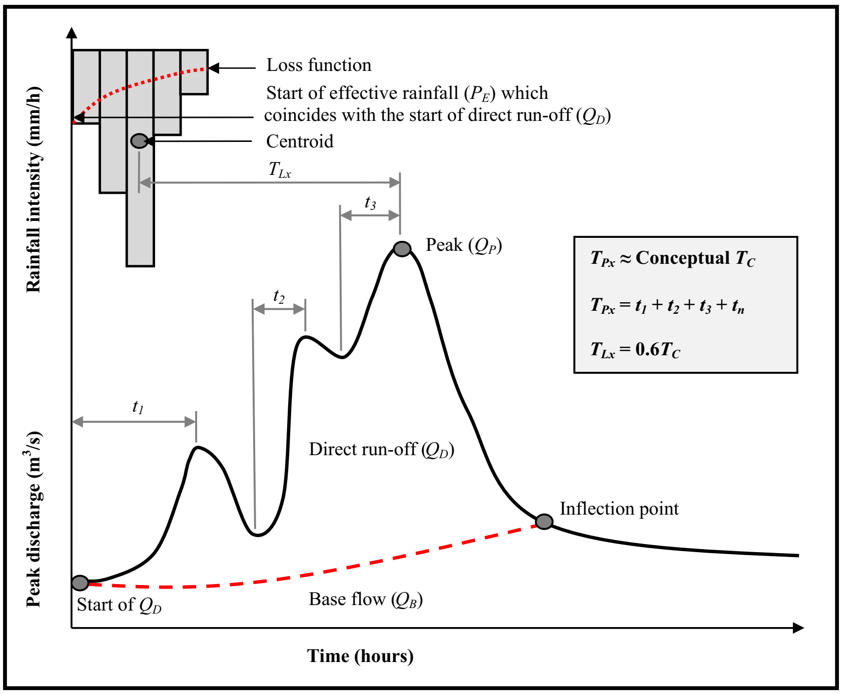

Figure 1 Schematic diagram illustrative of the relationships between the different catchment response time parameters (conceptual T_C, T_{Px} and T_{Lx}) for multi-peaked hydrographs.

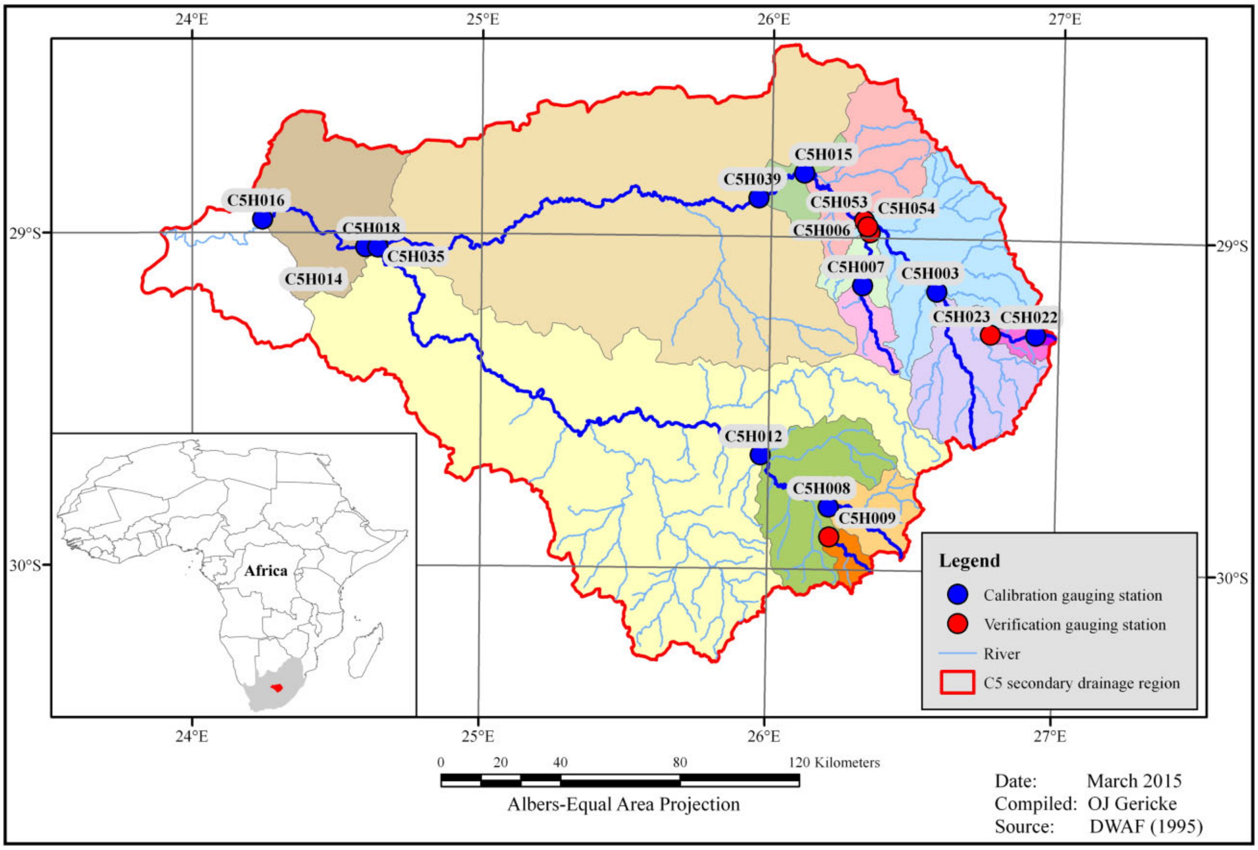

Figure 2 Location of the pilot study area (C5 secondary drainage region).

regions. The pilot study area is situated in primary drainage Region C and comprises of the C5 secondary drainage region (Midgley *et al*., 1994). The location of the pilot study area is also shown in Figure 2 and has an area of 34 795 km^2 and is characterised by 99.1% rural areas, 0.7% urbanisation and 0.2% water bodies (DWAF, 1995). The natural vegetation is dominated by Grassland of the Interior Plateau, False Karoo and Karoo. Cultivated land is the largest human-induced land cover alteration in the rural areas, while residential and suburban areas dominate the urban areas (CSIR, 2001). The topography is gentle with slopes between 1.7% and 10.3% (USGS, 2002), and water tends to pond easily, thus influencing the attenuation and translation of floods. The average mean annual precipitation (MAP) for the C5 secondary drainage region is 424 mm, ranging from 275 mm in the west to 685 mm in the east (Lynch, 2004), and rainfall is characterised as highly variable and unpredictable. The rainy season starts in early September and ends in mid-April with a dry winter. The Modder and Riet Rivers are the main river reaches and discharge into the Orange–Vaal River drainage system (Midgley *et al*., 1994).

Methodology

In this section, a flow diagram (Figure 3) is used to provide a general overview of the methodology followed in this study. In addition, for sections denoted with ** in Figure 3, a detailed discussion is included below to provide further details and clarification on the methodology contained in Figure 3.

Analyses of flood hydrographs

As summarised in Figure 3, it is important to note that Smakhtin and Watkins (1997) adopted the methodology as proposed by Nathan and McMahon (1990) with some modifications for a national-scale study in SA. Subsequently, based on these recommendations, as well as the need for consistency and reproducibility, the above-mentioned three methods were considered in this study. The equations as proposed by Nathan and McMahon [1990; Eqn (2)] and Chapman [1999; Eqn (3)] are given by:

$$Q_{D(i)} = \alpha Q_{D(i-1)} + \beta(1+\alpha)\left(Q_{T(i)} - Q_{T(i-1)}\right) \quad (2)$$

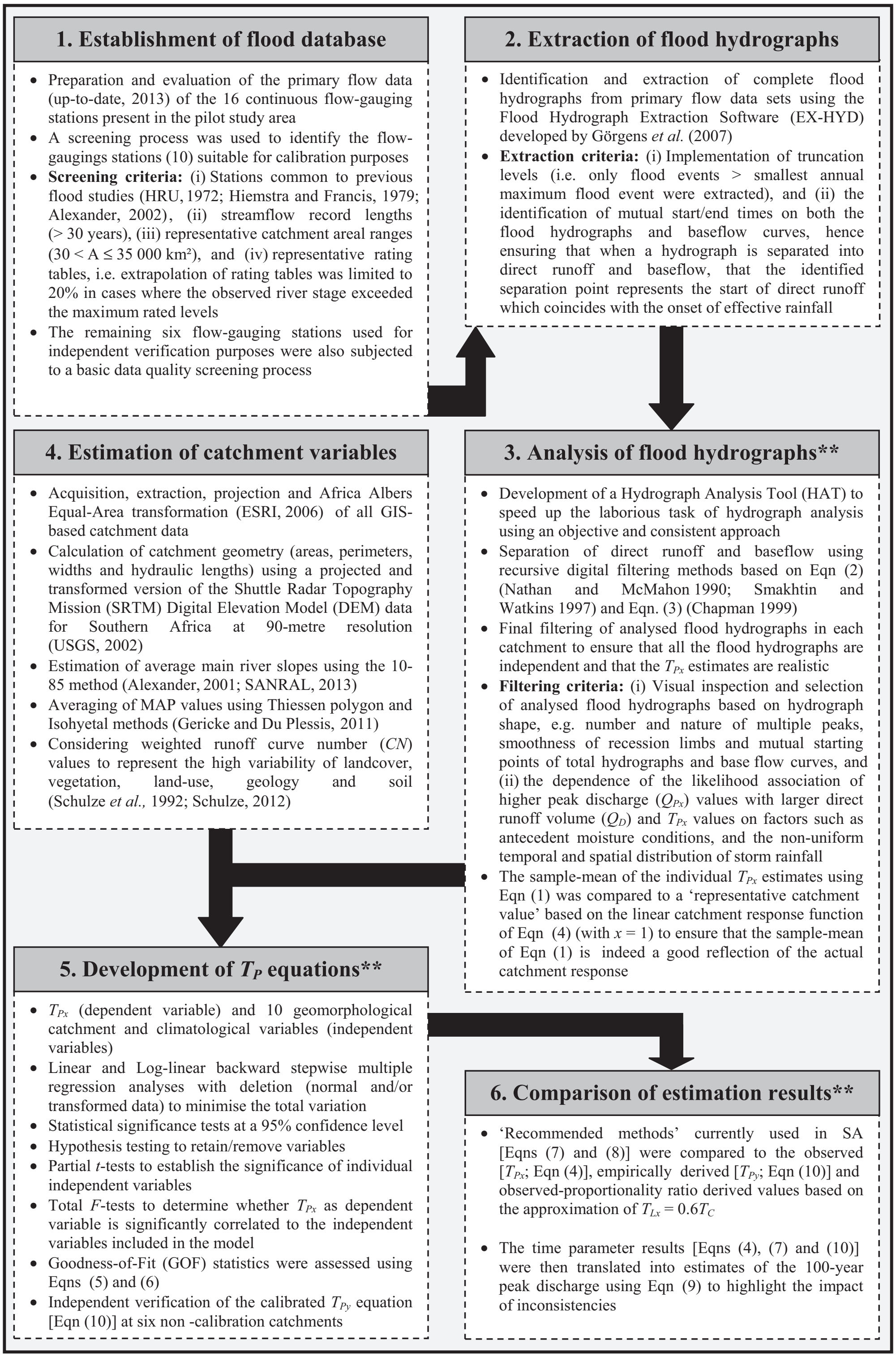

Figure 3 Schematic flow diagram illustrative of the implemented methodology.

$$Q_{D(i)} = \left(\frac{(3\alpha - 1)}{(3 - \alpha)}\right) Q_{D(i-1)} + \frac{2}{(3-\alpha)}\left(Q_{T(i)} - Q_{T(i-1)}\right) \quad (3)$$

where $Q_{D(i)}$ is the filtered direct run-off at time step i, which is subject to $Q_D \geq 0$ for time i (m^3/s), α,β are the filter parameters, and $Q_{T(i)}$ is the total stream flow (i.e. direct run-off plus base flow) at time step i (m^3/s).

In using Eqn (2) in their national-scale study in SA, Smakhtin and Watkins (1997) established that a fixed α-parameter of 0.995 is suitable to most catchments in SA, although in some catchments, α-values of 0.997 proved to be more appropriate. Hughes *et al.* (2003) also highlighted that a fixed β-parameter 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 to achieve an acceptable result. Subsequently, a fixed α-value of 0.995 was used in all the catchments under consideration. However, in some of the catchments with data sets having subdaily data with time intervals as short as 12 min (especially after the year 2000), the α-value of 0.995 resulted in a too high proportion of base flow relative to total flow. In such cases, the average base flow index (BFI) of the pre-2000 data years was used to adjust the base flow volumes accordingly. Comparable/similar results were obtained by increasing the α-parameter value to 0.997.

In addition to the filtering criteria listed in Figure 3, the relationship between the volume of direct run-off (Q_D) and observed peak discharge (Q_{Px}) was also investigated. The slope of the linear regression between corresponding Q_D and Q_{Px} values was computed using Eqn (4) for each catchment to provide an estimate of the observed catchment response time. Although, Eqn (4) assumes a linear catchment response function, it is very useful as a 'representative value' to ensure that the average of individual responses [using Eqn (1)] provides a good indication of the catchment conditions and sample mean. The need for and applicability of such an investigation was also highlighted by Schmidt and Schulze (1984). Schmidt and Schulze (1984) also regarded the averaging of observed time responses between effective rainfall and direct run-off for individual events to provide an index of catchment response, as impractical for peak discharge estimation. This also provides some justification for the use of this alternative approach, as initially suggested by Gericke and Smithers (2014).

$$T_{Avg} = \frac{1}{3600x}\left[\frac{\sum\left(Q_{Px} - \overline{Q_{Px}}\right)\left(Q_D - \overline{Q_D}\right)}{\sum\left(Q_{Px} - \overline{Q_{Px}}\right)^2}\right] \quad (4)$$

where T_{Avg} is the average observed catchment response time (T_{Px}, T_{Cx} or T_{Lx}; hours), Q_D is the volume of direct run-off (m^3), $\overline{Q_D}$ is the mean of Q_D (m^3), Q_{Px} is the observed peak discharge (m^3/s), $\overline{Q_{Px}}$ is the mean of Q_{Px} (m^3/s), and x is a variable proportionality ratio which depends on the catchment response time parameter under consideration, i.e. T_{Px} ($x = 1$), T_{Cx} ($x = 1$) and T_{Lx} ($x = 1.667$).

Development of T_P equations

The 10 independent geomorphological catchment and climatological variables, as referred to in Figure 3 and considered for possible inclusion are: (1) area (A, km^2), (2) perimeter (P, km), (3) hydraulic length (L_H, km), (4) main watercourse length (L_{CH}, km), (5) centroid distance (L_C, km), (6) average catchment slope (S, %), (7) average main watercourse slope (S_{CH}, %), (8) drainage density (D_D, km/km^2), (9) MAP (mm), and (10) weighted CN values (representative of land use and cover, and hydrological soil characteristics). The details of the coefficient of multiple correlation and the standard error of estimate as used to assess the GOF statistics, are shown by Eqns (5) and (6) (McCuen, 2005), respectively.

$$R_i^2 = \frac{\sum_{i=1}^{N}\left(\overline{\overline{y_i}} - \overline{y}\right)^2}{\sum_{i=1}^{N}\left(y_i - \overline{y}\right)^2} \quad (5)$$

$$S_E = \left[\frac{1}{v}\sum_{i=1}^{N}\left(\overline{\overline{y_i}} - y_i\right)^2\right]^{0.5} \quad (6)$$

where R_i is the multiple correlation coefficient for an equation with i independent variables, S_E is the standard error of estimate, y_i is the dependent variable, $\overline{y}$ is the mean of dependent variables, $\overline{\overline{y_i}}$ is the dependent variable (y_i) estimated from the best linear relationship with independent variable (x_i), i is the number of independent variables, N is the number of dependent variable observations (sample size), and v is the degrees of freedom (N- i, with y-intercept = 0).

Comparison of estimation results

The 'recommended methods' referred to in Figure 3, are shown in Eqn (7) (USBR, 1973) and Eqn (8) (HRU, 1972), respectively.

$$T_{Cy} = \left(\frac{0.87 L_H^2}{10 S_{CH}}\right)^{0.385} \quad (7)$$

$$T_{Ly1} = C_T\left(\frac{L_H L_C}{\sqrt{\frac{S_{CH}}{100}}}\right)^{0.36} \quad (8)$$

where T_{Cy} is the estimated channel flow time of concentration (hours), T_{Ly1} is the estimated lag time (hours), C_T is the regional storage coefficient (ranging from 0.19 to 0.32 in the C5 drainage region), L_C is the centroid distance (km), L_H is the hydraulic length of catchment (km), and S_{CH} is the average main watercourse slope (%).

The details of the standard design flood (SDF) method [Eqn (9); Alexander, 2002] as referred to in Figure 3, are as follows:

$$Q = 0.278\left[\frac{C_2}{100} + \left(\frac{Y_T}{2.33}\right)\left(\frac{C_{100}}{100} - \frac{C_2}{100}\right)\right] I_T A \qquad (9)$$

where Q is the design peak discharge (m^3/s), A is the catchment area (km^2), C_2 is the 2-year return period run-off coefficient (15% for pilot study area), C_{100} is the 100-year return period run-off coefficient (60% for pilot study area), I_T is the average design rainfall intensity (mm/h), and Y_T is the 100-year return period factor (2.33).

It is important to note that Eqn (9) is a regionally calibrated version of the rational method and is deterministic–probabilistic in nature and applicable to catchment areas up to 40 000 km^2 (Alexander, 2002; Gericke and Du Plessis, 2012; SANRAL, 2013).

Results and discussion

The results from the application of the above methodology are presented below. The station numbers of the Department of Water and Sanitation (DWS) flow-gauging stations located at the outlet of each catchment are used as catchment descriptors for easy reference in all the tables and figures. Subscripts 'x' and 'y' are used to distinguish between estimates from observed data (x) and predictions or estimates (y) using either the developed empirical time parameter equation (this study) or applying the 'recommended methods' as commonly used in SA.

Estimation of catchment variables

The general catchment attributes (e.g. climatological variables, catchment geomorphology, catchment variables and channel geomorphology) for each catchment in the pilot study area are listed in Table 1.

The influences of each variable or parameter listed in Table 1 are highlighted where applicable in the subsequent sections.

Establishment of flood database

The details of the 16 flow-gauging stations used during the establishment of the flood database are listed in Table 2. The average data record length in the pilot study area is 46 years.

Extraction of flood hydrographs

A total of 1134 complete flood hydrographs were extracted from the primary flow data sets, with between 13 and 117 individual flood hydrographs per flow-gauging station/catchment. An example of a typical flood hydrograph is illustrated in Figure 4.

Analyses of flood hydrographs

Due to the nature of flood hydrographs, it is important to note that the HAT software tool could not cater for all variations in flood hydrographs; hence a measure of user intervention was required, especially when T_{Px} was determined for multi-peaked hydrographs. Input to HAT is the extracted flood hydrographs obtained using the EX-HYD software (Görgens *et al.*, 2007), while the output includes the following: (1) start/end date/time of flood hydrograph, (2) observed peak discharge (Q_{Px}, m^3/s), (3) total volume of run-off (Q_T, m^3), (4) volume of direct run-off (Q_D, m^3), (5) volume of base flow (Q_B, m^3), (6) BFI, (7) depth of effective rainfall (P_E, mm); based on the assumption that the volume of direct run-off equals the volume of effective rainfall and that the total catchment area is contributing to run-off, (8)

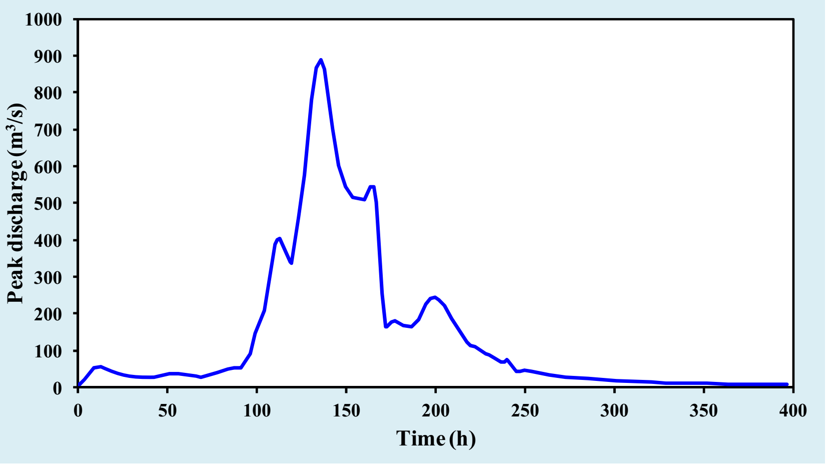

Figure 4 Example of extracted flood hydrograph at C5H015.

Table 1 General catchment information

Catchment descriptors	C5H003	C5H006	C5H007	C5H008	C5H009	C5H012	C5H014	C5H015	C5H016	C5H018	C5H022	C5H023	C5H035	C5H039	C5H053	C5H054
Climatological variables																
MAP (Thiessen polygon, mm)	559	524	508	462	477	449	435	522	430	461	675	648	461	519	531	524
MAP (Isohyetal, mm)	552	515	495	451	464	440	433	519	428	459	654	611	459	516	529	515
Catchment geomorphology																
Area (A, km^2)	1 641	676	346	598	189	2366	31 283	5939	33 278	17 361	39	185	17 359	6331	4569	687
Perimeter (P, km)	196	145	100	122	71	230	927	384	980	730	28	65	730	411	329	146
Hydraulic length (L_H, km)	71	64	41	41	24	87	326	160	378	375	8	29	373	187	120	68
Centroid distance (L_C, km)	41	29	17	22	14	45	207	81	230	174	3	17	173	103	56	33
Average catchment slope (S, %)	3.90	2.02	1.75	4.83	3.66	3.28	2.13	2.77	2.09	1.73	10.29	7.09	1.73	2.66	3.08	2.07
Catchment variables																
Urban areas/imperviousness (%)	2.18	12.54	1.19	0.00	0.00	0.07	0.70	2.72	0.66	1.18	0.00	0.02	1.18	2.55	3.42	12.34
Rural areas/perviousness (%)	95.09	85.91	97.57	99.11	98.83	98.78	95.93	95.17	96.04	94.64	98.22	97.08	94.64	94.94	94.59	86.06
Water bodies/DWS dams (%)	2.72	1.55	1.24	0.89	1.17	1.15	3.37	2.11	3.30	4.18	1.78	2.90	4.18	2.51	1.99	1.60
Weighted CN value	68.0	73.6	73.4	67.3	67.1	67.3	68.8	69.8	69.0	70.1	67.8	67.9	70.1	69.8	69.8	73.6
SDF run-off coefficient (T = 100-yr)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
HRU storage coefficient (C_T)	0.32	0.32	0.32	0.25	0.19	0.21	0.23	0.32	0.23	0.25	0.32	0.32	0.25	0.32	0.32	0.32
Channel geomorphology																
Main watercourse length (L_{CH}, km)	71	64	40	41	24	87	326	160	378	375	8	29	373	187	119	67
Total length of all the rivers (L, km)	380	123	66	104	37	431	3 320	1196	3 372	1 617	8	37	1 629	1 236	937	127
Avg. main river slope (S_{CH}, %)	0.26	0.27	0.34	0.49	0.60	0.27	0.10	0.14	0.10	0.08	1.70	0.58	0.08	0.13	0.18	0.26
Strahler catchment order	4	3	2	3	2	4	5	4	5	4	1	2	4	4	4	3
Shreve stream network magnitude	14	7	3	5	2	18	102	42	102	47	1	4	47	42	34	7
Drainage density (D_D, km/km^2)	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.2	0.2

Table 2 Information of catchments as included in the flood database

Catchment descriptor	Area (km²)	HRU (1972)	Hiemstra and Francis (1979)	Alexander (2002)	Record length		
					Start	End	Years
C5H003**	1 641	X			1918	2013	95
C5H006	676				1922	1926	4
C5H007**	346	X	X	X	1923	2013	90
C5H008**	598			X	1931	1986	55
C5H009	189				1931	1986	55
C5H012**	2 366	X	X	X	1936	2013	77
C5H014**	31 283				1938	2013	75
C5H015**	5 939		X	X	1949	1983	34
C5H016**	33 278				1953	1999	46
C5H018**	17 361				1960	1999	39
C5H022**	39				1980	2013	33
C5H023	185				1983	2008	25
C5H035	17 359				1989	2013	24
C5H039**	6 331				1970	2013	43
C5H053	4 569				1999	2013	14
C5H054	687				1995	2013	18

**, calibration flow-gauging stations. X, flow-gauging stations used in previous flood studies.

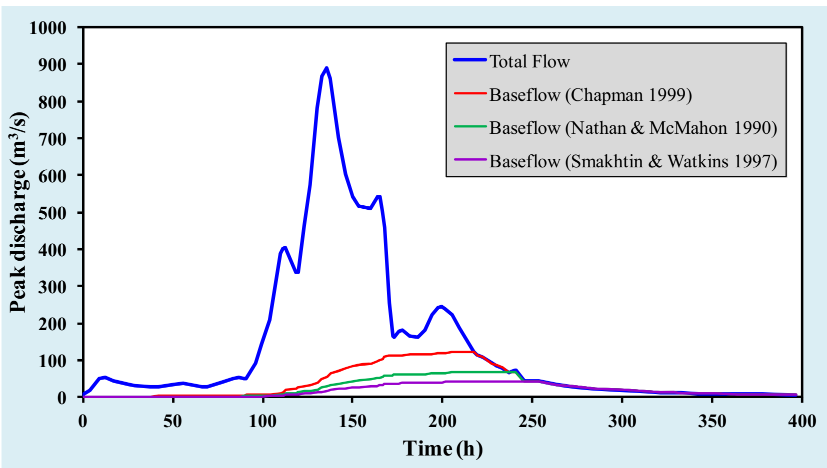

Figure 5 Example of the base flow separation results at C5H015.

time to peak (T_{Px}, hours), and (9) summary of results in different T_P ranges (both at a catchment and regional level).

Typical base flow separation results using the three recursive filtering methods are illustrated in Figure 5. The data series plots of Nathan and McMahon (1990) and Chapman (1999) are based on a fixed α-parameter value of 0.995, while the data series plot of Smakhtin and Watkins (1997) is based on a fixed α-parameter value of 0.997. This was specifically done to illustrate the flexibility in setting the α-parameter values, while the equations of Nathan and McMahon (1990) and Smakhtin and Watkins (1997) are identical. By considering both the recommendations made by Smakhtin and Watkins (1997) and Hughes *et al.* (2003), Eqn (2) was used to separate the direct run-off and base flow in this study.

The initial number (1 134) of extracted flood hydrographs was reduced to 935 following the final filtering process, as detailed in the Methodology summarised above and in Figure 3. Table 3 contains a summary of typical results as obtained using the HAT software at a catchment level (C5H015), after the individual filtering of all flood hydrographs. Figure 6 shows the scatter plot of corresponding Q_{Px} and T_{Px} [using Eqn (1)] values at catchment C5H015.

It is evident from Table 3 that, as expected, the largest average T_{Px} values are associated with the maximum direct run-off volumes. Taking the bigger average P_E values in the T_P ranges into consideration, the likelihood of the entire catchment receiving rainfall for the critical storm duration becomes a more realistic assumption. Subsequently, the

Table 3 Typical summary of hydrograph analysis results using the HAT at C5H015

Catchment information	T_P range (h)	Number of events	Averages associated with each T_P range					
			Q_T (10^6 m^3)	Q_D (10^6 m^3)	Q_{Px} (m^3/s)	T_{Px} [Eqn (1), h]	P_E (mm)	BFI
C5H015	$0 \leq 5$	5	13.6	12.1	113.5	4.1	2.0	0.1
	$6 \leq 10$	14	10.0	9.1	113.3	7.8	1.5	0.1
	$11 \leq 15$	6	17.1	15.0	142.7	13.4	2.5	0.1
Area: 5 939 km^2	$16 \leq 20$	9	15.3	13.5	130.6	17.9	2.3	0.1
	$21 \leq 30$	21	15.1	13.4	121.0	25.6	2.3	0.1
Data period: 1949/01/01 to	$31 \leq 40$	14	21.7	18.9	200.2	33.8	3.2	0.1
1983/11/22	$41 \leq 50$	13	38.3	35.6	337.9	43.3	6.0	0.1
	$51 \leq 75$	8	66.1	60.4	544.3	57.4	10.2	0.1
Averages/totals		**90**	**23.3**	**21.0**	**203.1**	**26.7**	**3.5**	**0.1**

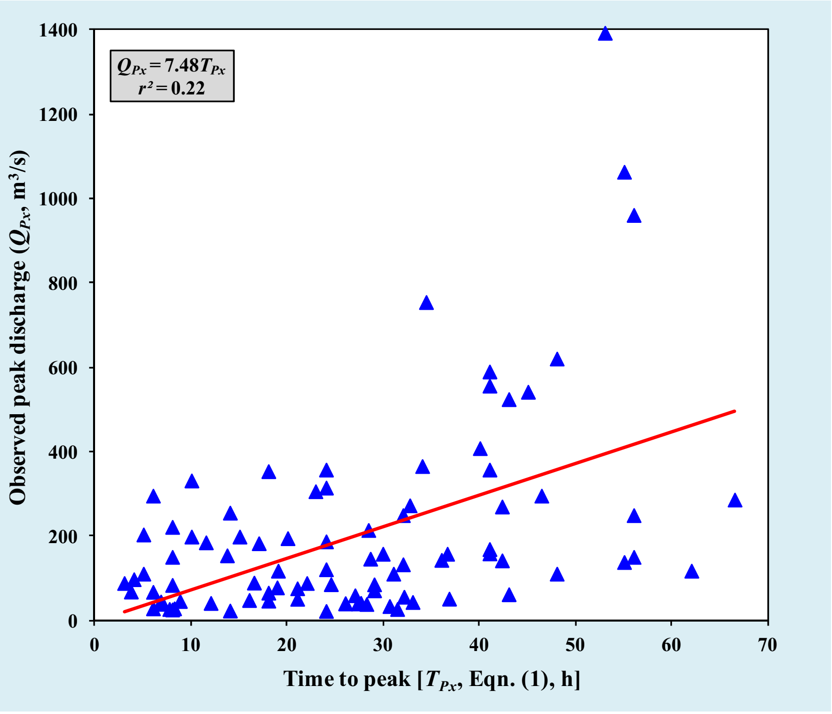

Figure 6 Scatter plot of Q_{Px} versus T_{Px} [Eqn (1)] at C5H015.

lower limit T_{Px} values could be expected when effective rainfall of high average intensity does not cover the entire catchment, especially when a storm is centered near the outlet of a catchment. However, from the results in Figure 6, similar trends are evident, but the variability between individual catchment responses and corresponding peak discharge values become more obvious and also highlight that the use of averages could be misleading and not always representative of the actual catchment processes. For example, lower limit T_{Px} values occurring more frequently and will thus incorrectly have a larger influence on the average value which will result in an under-estimated catchment T_{Px} value. 'High outliers' occurring less frequently are not as problematic, because at medium to large catchment scales, the contribution of the whole catchment to peak discharge seldom occurs due to the spatial and temporal distribution of rainfall. In principal, these events are actually required to adhere to the conceptual definition of T_C ($\approx T_P$), which assumes that T_C is the time required for run-off, generated from effective rainfall with a uniform spatial and temporal distribution over the whole catchment, to contribute to the peak discharge at the catchment outlet. Similar results as contained in Table 3 and Figure 6 were also evident in all the other 15 catchments under consideration and support the use of Eqn (4) as a catchment 'representative value', which is discussed in the next paragraph and shown in Figure 7.

Figure 7 shows a typical scatter plot of corresponding Q_D and Q_{Px} values at catchment C5H015. The slope of the

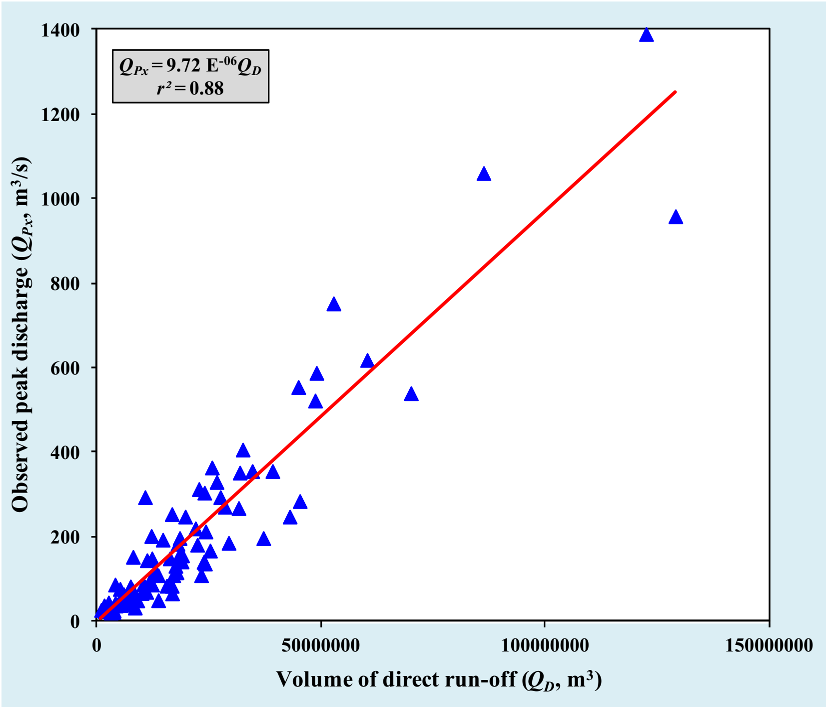

Figure 7 Scatter plot of Q_{Px} versus Q_D at C5H015.

linear trend line equals T_{Px} and is computed using Eqn (4) with a proportionality ratio $(x) = 1$. In using Eqn (4) at a catchment level, and as illustrated in Figure 7, a moderate to acceptable degree of association (r^2 values ranging from 0.50 to 0.98) was obtained between the corresponding Q_D and Q_{Px} values in all the other 15 catchments under consideration.

A scatter plot of the T_{Px} pair values based on the use of Eqns (1) and (4), respectively, and associated with all the catchments under consideration is shown in Figure 8.

The results illustrated in Figure 8 indicate a high degree of association, with an average T_{Px4}/T_{Px1} ratio of 1.12 and r^2 value = 0.97. The T_{Px4} values [Eqn (4) with $x = 1$] are generally larger than the T_{Px1} values [Eqn (1)], with only 25% of the catchments characterised by T_{Px4}/T_{Px1} ratios of $\leq$ 1. The individual T_{Px4}/T_{Px1} ratios vary between −6% and +44%. The differences in estimated catchment response time must be viewed in the context of the actual travel time associated with the size of a particular catchment, as the impact of a 10% difference in estimates might be critical in a small catchment, while being less significant in a larger catchment. It is evident that these percentage differences are not correlated to the catchment area. The average slope descriptors (S and S_{CH}) in the different catchments are very similar, hence their insignificant potential influence on the results. Other catchment shape parameters, such as the circularity ratio, expressed as $P/\sqrt{4\pi A}$ and the ratio of L_C: L_H, also proved to have an insignificant influence on the results. However, the catchments characterised by T_{Px4}/T_{Px1} ratios $\leq$ 1 also had L_C: L_H ratios < 0.5, hence the association between the shorter centroid distances and lower T_{Px4} values.

A summary of the average catchment conditions based on the individual analysis in each catchment is listed in Table 4.

Development of T_P equations

The backward stepwise multiple linear regression analyses using untransformed data showed promising results, however, some predictions in both the calibration and verification catchments resulted in negative values. In the case of transformed data, power-transformed independent variables, e.g. $y = ax^b$, resulted in the highest degree of association when individually plotted against the dependent variables, although when included as part of the multiple regression analyses, the transformed independent variables performed less satisfactorily. Backward stepwise multiple Log-linear regression analyses with deletion based on an exponential distribution resulted in the best prediction model for T_{Py}. The following independent variables were retained and included in the calibrated equation: (1) MAP, (2) area, (3) centroid distance, (4) hydraulic length, and (5) average catchment slope. At a confidence level of 95%, all the above independent variables contributed significantly towards the prediction accuracy. In addition to being statistically significant, the retained independent variables are also regarded as both conceptually and physically acceptable, i.e.

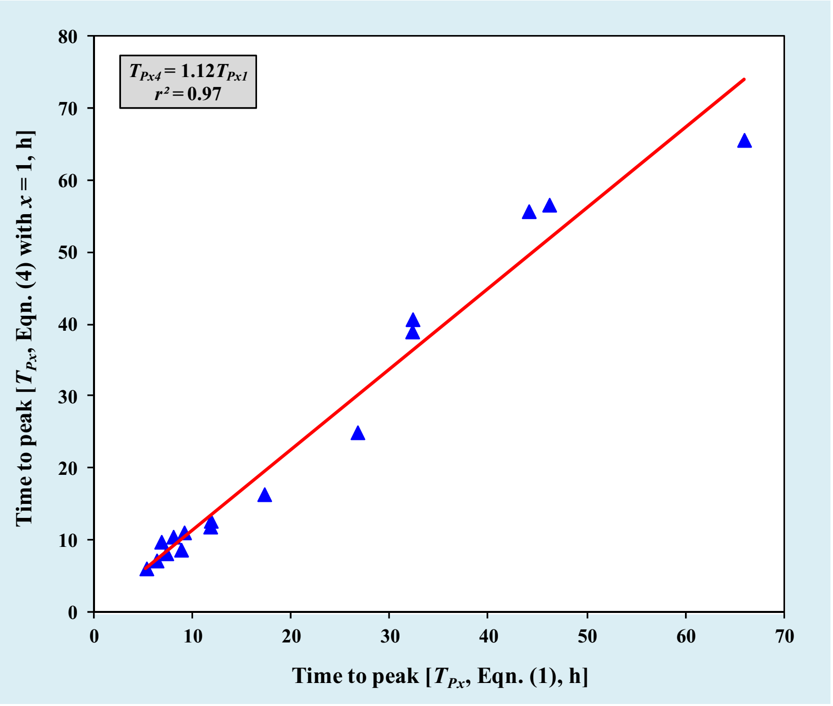

Figure 8 Scatter plot of T_{Px} [Eqn (4) with $x = 1$] versus T_{Px} [Eqn (1)] in all the catchments.

Table 4 Summary of average catchment results in the C5 secondary drainage region

Catchment	Data period	Number of events	Average catchment values: Q_T (10^6 m^3)	Q_D (10^6 m^3)	Q_{Px} (m^3/s)	T_{Px} [Eqn (1), h]	T_{Px} [Eqn (4), h]	P_E (mm)	BFI
C5H003	1918/07/01 to 2013/06/26	101	2.1	1.7	32.8	9.1	11.1	1.0	0.2
C5H006	1922/11/13 to 1926/12/31	14	1.4	1.3	36.0	7.3	8.2	1.9	0.1
C5H007	1923/10/01 to 2013/08/06	91	1.2	1.0	28.0	6.4	7.2	2.9	0.1
C5H008	1931/04/01 to 1986/04/01	112	2.2	2.0	44.7	8.0	10.5	3.3	0.1
C5H009	1931/03/01 to 1986/05/11	13	1.0	0.8	14.3	11.8	12.7	4.5	0.1
C5H012	1936/04/01 to 2013/02/13	68	3.3	2.3	41.5	11.8	11.9	1.0	0.3
C5H014	1938/10/17 to 2013/07/25	28	46.7	36.5	168.3	46.2	56.6	1.2	0.2
C5H015	1949/01/01 to 1983/11/22	90	23.3	21.0	203.1	26.7	30.9	3.5	0.1
C5H016	1953/02/01 to 1999/03/10	40	31.0	27.0	105.6	65.9	65.6	0.8	0.1
C5H018	1960/02/23 to 1999/03/15	50	22.8	19.7	105.0	32.3	39.0	1.1	0.1
C5H022	1980/10/14 to 2013/10/24	69	0.4	0.3	11.5	5.3	6.1	8.0	0.2
C5H023	1983/06/04 to 2008/03/22	58	0.8	0.6	15.6	6.8	9.8	3.3	0.2
C5H035	1989/08/03 to 2013/07/23	20	10.8	9.1	58.9	32.3	40.7	0.5	0.2
C5H039	1970/11/24 to 2013/08/08	56	34.0	29.2	136.2	44.1	55.7	4.6	0.1
C5H053	1999/11/29 to 2013/08/08	65	8.3	5.7	93.1	17.3	16.4	1.3	0.3
C5H054	1995/10/18 to 2013/08/08	60	1.3	0.8	21.3	8.8	8.7	1.2	0.4

the shape (A), distance (L_C and L_H) and slope (S) predictors arguably provide a good indication of catchment storage effects (attenuation and travel time), while the MAP incorporates the rainfall variability. In addition, the five independent variables also meet the requirement of consistency and user-friendliness, especially when different practitioners need to determine the variables in ungauged catchments. The derived T_{Py} regression is shown in Eqn (10):

$$T_{Py} = (1.00321)^{MAP}(0.99984)^{A}(1.05999)^{L_C}(0.98663)^{L_H}(0.97615)^{S} \tag{10}$$

where T_{Py} is the predicted time to peak (hours), A is the catchment area (km^2), L_C is the centroid distance (km), L_H is the hydraulic length (km), MAP is the mean annual precipitation (mm), and S is the average catchment slope (%).

A summary of the GOF statistics and hypothesis testing results is listed in Table 5.

The results contained in Table 5 are based on the output generated using the HAT software. The predictions based on Eqn (10) showed a high degree of association with the observed values (both for calibration and independent verification), with the standard error of the T_{Py} estimate = 5.3 h and an associated coefficient of multiple correlation = 0.95. The rejection of the null hypothesis ($F > F_{\alpha}$, with $F_{\alpha} = 5.1$) confirmed that T_{Py} ($F = 244$) as dependent variable is related significantly to the independent variables as included in the regression model.

Although Eqn (10) meets the requirement of consistency and user-friendliness, it has potential limitations, especially in terms of its application in ungauged catchments beyond the boundaries of the pilot study area. Therefore, the methodology followed in this study should be expanded to other SA study areas in different climatological regions, followed by regionalisation. The regionalisation will improve and augment the accuracy of the time parameter estimates, while warranting the combination and transfer of information within the identified homogeneous hydrological regions. Typically, a clustering method (Hosking and Wallis, 1997) could be used, which utilises the geomorphological catchment characteristics and flood statistics to establish the regions and to test the homogeneity, respectively.

It is also important to compare the results obtained with the generally accepted time parameter definitions and proportionality ratios for small catchments as documented in the literature, since both have a large influence on the inconsistency between different methods. In using T_{Lx} defined as the time from the centroid of effective rainfall to the centroid of direct run-off, T_{Lx} and the conceptual T_C ($\approx T_{Px}$) can be related by $T_L = 0.705T_C$ (McCuen, 2009). In using T_{Lx} defined as the time from the centroid of effective rainfall to the time of the peak discharge of total or direct run-off, the proportionality ratio decreases to 0.6 (McCuen, 2009) as illustrated in Figure 1. In acknowledging that $T_C \approx T_P$ and $T_L = 0.6T_C$, the latter proportionality ratio of 0.6 could also be applied to Eqns (4) and (10) to provide an indication of the observed T_{Lx} and predicted T_{Ly2} values respectively as listed in Table 6.

In comparing the results based on Eqn (8) to the T_{Lx} values in both the calibration and verification catchments, the T_{Ly1} values were overestimated in ± 90% of the catchments and overestimations of up to 186% were evident. The underestimations were limited to −49%. However, the above-mentioned T_{Lx} definition with an associated proportionality ratio of 0.6, is also used in literature (McCuen, 2009; Gericke and Smithers, 2014) to define T_{Cx}, thus by

Table 5 Summary of GOF statistics and hypothesis testing results

Criterion	T_{Py} [Eqn (10)] results
Number of observations (N)	10
Confidence level ($1 - \alpha$) (%)	95
Coefficient of determination (r^2)	0.99
Coefficient of multiple-correlation [Eqn (5)]	0.95
Standard error of estimate [Eqn (6), h]	5.34
F-Observed value (F-statistic)	243.81
Probability of F-statistic	5.77 E^{-05}
Critical F-statistic (F_{α})	5.05

Table 6 Calibration and verification T_L results based on a proportionality ratio of 0.6

Catchment descriptor	T_{Lx} observed [Eqn (4), $x = 1.667$, h]	T_{Ly1} estimated [Eqn (8), h]	T_{Ly2} predicted [$0.6 \times$ Eqn (10), h]	T_{Ly1}/T_{Lx} ratio	T_{Ly2}/T_{Lx} ratio
Calibration					
C5H003	6.7	16.6	10.3	2.49	1.54
C5H007	4.3	9.5	4.2	2.19	0.98
C5H008	6.3	7.6	4.4	1.21	0.69
C5H012	7.1	11.8	6.7	1.65	0.94
C5H014	34.0	43.2	31.2	1.27	0.92
C5H015	18.5	31.4	14.7	1.70	0.79
C5H016	39.4	46.9	42.4	1.19	1.08
C5H018	23.4	49.3	25.0	2.11	1.07
C5H022	3.7	2.0	4.0	0.55	1.09
C5H039	33.4	37.0	33.9	1.11	1.01
Verification					
C5H006	4.9	14.0	6.2	2.86	1.26
C5H009	7.6	3.9	3.8	0.51	0.50
C5H023	5.9	7.6	6.5	1.30	1.10
C5H035	24.4	49.0	23.2	2.01	0.95
C5H053	9.8	23.8	7.5	2.42	0.76
C5H054	5.2	14.9	7.1	2.86	1.36

implication, $T_C \approx T_L$. In agreement with the latter implication, but in contradiction to other literature, Schultz (1964) also established that for catchments in Lesotho and SA, $T_C \approx T_L$. Taking cognisance of this, the proportionality ratio of 0.6 then increases to unity. Thus, by comparing the results based on Eqn (8) to the T_{Px} (instead of T_{Lx}) values in both the calibration and verification catchments, the overestimation of T_{Ly1} are reduced to 72%, while the underestimations are slightly increased to −69%. These improved results also suggest and support the approximation of $T_C \approx T_L$ at these catchment scales. Furthermore, Eqn (8) was locally developed by the HRU (1972) for application in catchment areas ranging from 50 to 5000 km^2 which is within the areal range classified as medium in this study.

These results, as well as Schultz's (1964) results support the argument that the suggested proportionality ratios are all based on research conducted in a limited number of small catchments. In small catchments, the exact occurrence of the maximum peak discharge is of more importance as opposed to larger catchments where flood volumes are central to the design. In addition, the simplifications used in small catchments are not applicable in real, large heterogeneous catchments where antecedent moisture from previous rainfall events and spatially non-uniform run-off producing rainfall hyetographs can result in multi-peaked hydrographs. Furthermore, Gericke and Smithers (2014) also argued that the accuracy of T_L estimation is, in general, so poor that differences in the T_L and T_C starting and ending points are insignificant. The use of these multiple time parameter definitions, combined with the fact that no 'standard method' could be used to estimate time parameters from observed hyetographs and hydrographs, emphasise why the proportionality ratio of T_L: T_C could typically vary between 0.5 and 2 for the same catchment.

The verification of the derived regression [Eqn (10)] to estimate T_{Py} and a comparison with values estimated using the 'recommended methods', are discussed in the following section.

Comparison of estimation results

The average observed T_P values (T_{Px}) estimated from the extracted flood hydrographs using Eqn (4) with $x = 1$, the predicted T_P values (T_{Py}) using Eqn (10) and T_C ($\approx T_P$) based on Eqn (7) and denoted as T_{Cy}, are all listed in Table 7. The 100-year design peak discharges computed using Eqn (9) are also included in Table 7 to reflect the translation of the different time parameters into peak discharge values. Both the calibration and verification results are shown. The relationship between the estimated (y) and observed (x) time parameters (T_Y/T_X) and resulting peak discharge ratios (Q_Y/Q_X) are shown in Figures 9 (calibration) and 10 (verification), respectively.

The results contained in Table 7 and illustrated in Figures 9 and 10 are characterised by several trends. In applying Eqn (7) in both the calibration and verification catchments, the T_{Cy} values were underestimated and overestimated with between −74% and +155% in comparison to the T_{Px} values, while the degree of association (r^2 value) was 0.75. The T_{Py} predictions based on Eqn (10) showed a high degree of association with the observed T_{Px} values during the calibration and verification process, with r^2 values ranging

Table 7 Calibration and verification time parameter and peak discharge results

Catchment descriptor	T_{Px} observed [Eqn (4), $x = 1$, h]	T_{Cy} estimated [Eqn (7), h]	T_{Py} predicted [Eqn (10), h]	Q_{TPx} (m^3/s)	Q_{TCy} (m^3/s)	Q_{TPy} (m^3/s)
Calibration						
C5H003	11.1	17.6	17.1	3 005	1 894	1 946
C5H007	7.2	10.3	7.0	901	631	922
C5H008	10.5	9.0	7.3	973	1 133	1 409
C5H012	11.9	20.1	11.2	3 967	2 350	4 203
C5H014	56.6	81.3	52.1	15 147	10 542	16 468
C5H015	30.9	41.1	24.5	4 536	3 414	5 731
C5H016	65.6	90.8	70.6	13 742	9 931	12 764
C5H018	39	99.4	41.6	12 934	5 076	12 130
C5H022	6.1	1.6	6.6	84	323	77
C5H039	55.7	48.5	56.4	2 668	3 061	2 633
Verification						
C5H006	8.2	16.0	10.4	1 932	989	1 529
C5H009	12.7	5.5	6.4	261	600	518
C5H023	9.8	6.5	10.8	228	344	207
C5H035	40.7	98.9	38.6	12 393	5 098	13 053
C5H053	16.4	30.1	12.5	5 619	3 059	7 358
C5H054	8.7	16.8	11.9	1 551	801	1 136

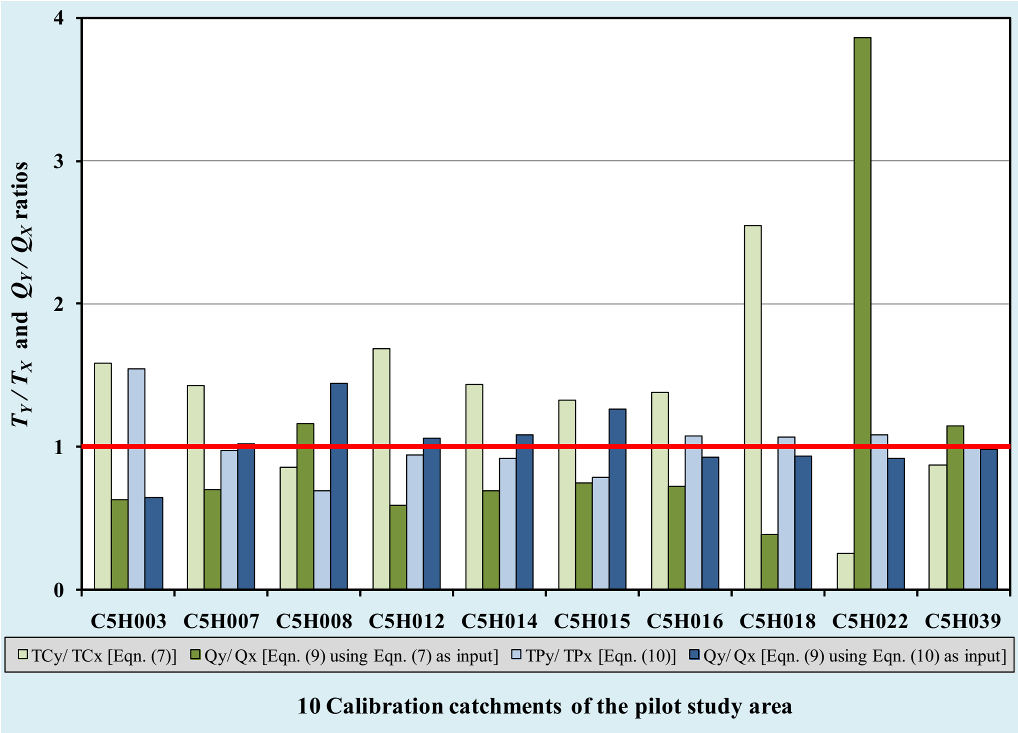

Figure 9 Calibration: Time parameter (T_Y/T_X) and peak discharge (Q_Y/Q_X) ratios.

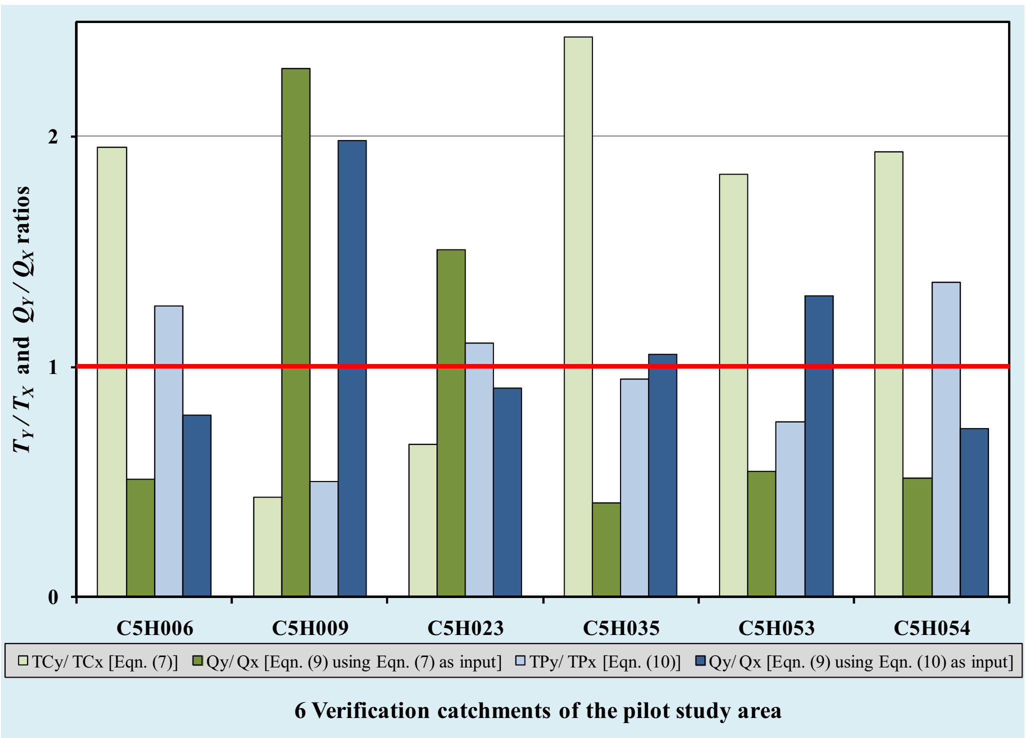

Figure 10 Verification: Time parameter (T_Y/T_X) and peak discharge (Q_Y/Q_X) ratios.

from 0.97 (calibration) to 0.91 (verification) and estimates of between −50% and +54% (Figures 9 and 10). The fact that Eqn (10) provided similar results during the verification phase confirms the reliability of time parameters estimated using Eqn (10).

In translating the corresponding time parameter estimation 'errors' to design peak discharges using the SDF method [Eqn (9)], the significance is evident. The underestimation of T_P (conceptual T_C) is associated with the overestimation of peak discharges and vice versa, *viz.* the overestimation of T_P results in underestimated peak discharges. It clearly evident from Figures 9 and 10 that the time parameter underestimations ranging from −2% to −74% are likely to result in peak discharge overestimations of between +2% and +286%, while time parameter overestimations of up to +155% could result in peak discharge underestimations of −61%.

Conclusions

The developed empirical equation to estimate the catchment response time at a medium to large catchment scale in the C5 secondary drainage region in SA meets the requirement of consistency and user-friendliness. Independent verification tests confirmed the consistency, while the statistical significant independent variables retained provide a good indication of catchment storage effects. These independent variables are also easy to determine by different practitioners when required for future applications in ungauged catchments. The developed empirical equation also highlighted the inherent limitations and inconsistencies introduced when the 'recommended' empirical methods are applied outside their bounds. However, the developed empirical equation also has potential limitations, especially in terms of its application in ungauged catchments beyond the boundaries of the pilot study area. Therefore, the methodology followed in this study should be expanded to other climatologically different regions in SA, followed by regionalisation. Adopting the approximation of $T_C \approx T_P$ using only observed stream flow data, confirmed that the design accuracy of any time parameter obtained from observed hyetographs or hydrographs depends on the computational accuracy of the corresponding input variables. The proposed T_{Px} estimation procedure based on a linear catchment response function [Eqn (4) with $x = 1$] and which is reliant on only observed stream flow variables, not only demonstrated a high degree of association with the sample means of T_{Px} [Eqn (1)], but such a procedure is also less influenced by the paucity of rainfall data and non-uniform spatial and temporal rainfall distribution in medium to large catchments. Furthermore, the similarity in the conceptual T_C, T_P and T_L estimates also questions the proposed use of the multiple time parameter definitions found in literature. The use of such multiple time parameter definitions, combined with the absence of a 'standard method' to estimate time parameters from observed data, emphasise why the proportionality ratio of T_L: T_C could typically vary between 0.5 and 2 for the same catchment/region.

Given the sensitivity of design peak discharges to estimated time parameter values, the use of inappropriate time variables results in overestimated or underestimated time parameters in South African flood hydrology practice and highlights that considerable effort is required to ensure that time parameter estimations are representative and consistently estimated. In general terms, such underestimations or overestimations of the peak discharge may result in the over-design or under-design of hydraulic structures, with associated socio-economic implications, which might render some projects as infeasible.

Building upon the critical assessment of available definitions, estimation procedures and the results from this pilot study, the current approaches used for the estimation of time parameters in medium to large catchments in SA could be modernised by implementing the identified research values. For instance, the results suggest that the methodology, based on the approximation of $T_P \approx T_C$, should be expanded to other study areas in different climatological regions in SA, followed by a clustered regionalisation scheme. It is also expected that the adopted catchment response estimation procedures and indentified similarities between time parameters could both improve and simplify the estimation of catchment response time at this level. Ultimately, such an extensive study will contribute fundamentally to both improved time parameter and peak discharge estimations at large catchment scales.

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References

Alexander W.J.R. *Flood risk reduction measures: Incorporating flood hydrology for Southern Africa*. Pretoria: Department of Civil and Biosystems Engineering, University of Pretoria, 2001.

Alexander W.J.R. The standard design flood. *J South Afr Inst Civ Eng* 2002, **44**, (1), 26–30.

Chapman T. A comparison of algorithms for streamflow recession and baseflow separation. *Hydrol Process* 1999, **13**, 701–714.

CSIR. GIS data: classified raster data for national coverage based on 31 landcover types. Pretoria: National Landcover database, Council for Scientific and Industrial Research, Environmentek, 2001.

Du Plessis D.B. Documentation of the March–May 1981 floods in the south-eastern Cape. Pretoria: Department of Water Affairs and Forestry, Technical Report No. TR120, 1984.

DWAF. GIS data: drainage regions of South Africa. Pretoria: Department of Water Affairs and Forestry, 1995.

ESRI. ArcGIS desktop help: map projections and coordinate systems. Redlands, CA: Environmental Systems Research Institute, 2006.

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

Gericke O.J. & Du Plessis J.A. Evaluation of the standard design flood method in selected basins in South Africa. *J S Afr Inst Civ Eng* 2012, **54**, (2), 2–14.

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

Görgens A.H.M., Lyons S., Hayes L., Makhabane M. & Maluleke D. Modernised South African design flood practice in the context of dam safety. Pretoria: Water Research Commission, WRC Report No. 1420/2/07, 2007.

Heggen R. Time of concentration, lag time and time to peak [online]. In: B. Shrestha & R. Rajbhandari, eds. *Proceedings of regional training course: application of geo-informatics for water resources management*. Kathmandu, Nepal: International Centre for Integrated Mountain Development, 2003, 3.1–3.23. Available from: http://www.hkh-friend.net.np/rhdc/training/lectures/heggen/Tc.pdf [30 September 2010].

Hiemstra L.A. & Francis D.M. *The Runhydrograph: theory and application for flood predictions*. Pretoria: Water Research Commission, 1979.

Hosking J.R.M. & Wallis J.R. *Regional frequency analysis: an approach based on L-moments*. Cambridge, UK: Cambridge University Press, 1997.

HRU. Design flood determination in South Africa. Johannesburg: Hydrological Research Unit, University of the Witwatersrand, Report No. 1/72, 1972.

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

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

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

Larson C.L. A two phase approach to the prediction of peak rates and frequencies of runoff for small ungauged watersheds. Stanford: Department of Civil Engineering, Stanford University, Technical Report No. 53, 1965.

Linsley R.K., Kohler M.A. & Paulhus J.L.H. Relationship between precipitation and run-off. In: S.I. Metric, ed. *Hydrology for engineers*. Singapore: McGraw-Hill, 1988, Chp. 8, pp. 221–249.

Lynch S.D. Development of a raster database of annual, monthly and daily rainfall for Southern Africa. Pretoria: Water Research Commission, WRC Report No. 1156/1/04, 2004.

McCuen R.H. *Hydrologic analysis and design*, 3rd ed. New York: Prentice-Hall, 2005.

McCuen R.H. Uncertainty analyses of watershed time parameters. *J Hydrol Eng* 2009, **14**, (5), 490–498.

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

Midgley D.C., Pitman W.V. & Middleton B.J. Surface water resources of South Africa. Volume 2, Drainage Region C. Pretoria: Water Research Commission, WRC Report No. 298/2.1/94, 1994.

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

Papadakis K.N. & Kazan M.N. Time of concentration in small rural watersheds. In: *Proceedings of the ASCE Engineering Hydrology Symposium*. Williamsburg, VA: ASCE, 633–638, 1987.

Pullen R.A. Synthetic unitgraphs for South Africa. Johannesburg: Hydrological Research Unit, University of the Witwatersrand, Report No. 3/69, 1969.

Sabol G.V. Lag relations for semi-arid regions and urban areas. In: *Proceedings of the ASCE Engineering Hydrology Symposium*. San Francisco, CA: ASCE, 168–173, 1993.

SANRAL. *Drainage manual*, 6th ed. Pretoria: South African National Roads Agency Limited, 2013.

Schmidt E.J. & Schulze R.E. Improved estimation of peak flow rates using modified SCS lag equations. Pietermaritzburg: Department of Agricultural Engineering, University of Natal, ACRU Report No. 17, 1984.

Schultz G.A. Studies in flood hydrograph synthesisation. Dissertation (MSc). Johannesburg: University of the Witwatersrand, 1964.

Schulze R.E. Mapping hydrological soil groups over South Africa for use with the SCS-SA design hydrograph technique: methodology and results. *Proceedings, 16th SANCIAHS Hydrology Symposium*, 1–3 October 2012. Pretoria: University of Pretoria, 2012.

Schulze R.E., Schmidt E.J. & Smithers J.C. SCS-SA user manual: PC-based SCS design flood estimates for small catchments in Southern Africa. Pietermaritzburg: Department of Agricultural Engineering, University of Natal, ACRU Report No. 40, 1992.

Seybert T.A. *Stormwater management for land development: methods and calculations for quantity control*. Hoboken, NJ: John Wiley and Sons Incorporated, 2006.

Smakhtin V.U. & Watkins D.A. Low flow estimation in South Africa. Pretoria: Water Research Commission, WRC Report No. 494/1/97, 1997.

USBR. *Design of small dams*, 2nd ed. Washington, DC: United States Bureau of Reclamation, Water Resources Technical Publications, 1973.

USDA NRCS. Time of concentration. In: D.E. Woodward, C.C. Hoeft, A. Humpal & G. Cerrelli, eds. *National engineering handbook*. Washington, DC: United States Department of Agriculture Natural Resources Conservation Service, 2010, pp. 1–18. Ch. 15 (Section 4, Part 630).

USDA SCS. Hydrology. In: K.M. Kent *et al*., eds. *National engineering handbook*. Washington, DC: United States Department of Agriculture Soil Conservation Service, 1985, pp. 1–23. Ch. 16 (Section 4).

USGS. *SRTM topography* [online]. United States Geological Survey. 2002. Available from: http://dds.cr.usgs.gov/srtm/version2.1/Documentation/SRTM/Topo.pdf [2 June 2010].

Watt W.E. & Chow K.C.A. A general expression for basin lag time. *Can J Civ Eng* 1985, **12**, 294–300.

