TECHNICAL PAPER

JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING

Vol 58 No 1, March 2016, Pages 2–15, Paper 1261

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Keywords: catchment response time, lag time, peak discharge, time of concentration, time to peak

Are estimates of catchment response time inconsistent as used in current flood hydrology practice in South Africa?

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Catchment response time parameters are one of the primary inputs required when design floods, especially in ungauged catchments, need to be estimated. The time of concentration (T_C) is the most frequently used time parameter in flood hydrology practice, and continues to find application in both event-based methods and continuous hydrological models. Despite the widespread use of the T_C, a unique working definition and equation(s) are currently lacking in South Africa. This paper presents the results of the direct and indirect T_C estimation for three sets of catchments, which highlight their inherent variability and inconsistencies. These case studies demonstrate that estimates of T_C, using different equations, may differ from one another by up to 800%. As a consequence of this high variability and uncertainty, we recommend that, for design hydrology and calibration purposes, observed T_C values should be estimated using both the average catchment T_C value, which is based on the event means, and a linear catchment response function. This approach is not only practical, but also proved to be objective and consistent in the study areas investigated in this paper.

INTRODUCTION

Design flood events, i.e. floods characterised by a specific magnitude–frequency relationship at a particular site, are very sensitive to the estimated time parameter values. Various researchers (e.g. Bondelid *et al* 1982; McCuen *et al* 1984; McCuen 2009) demonstrated that as much as 75% of the total error in estimates of peak discharge could be ascribed to errors in the estimation of time parameters. Gericke and Smithers (2014) showed that the underestimation of time parameters by 80% or more could result in the overestimation of peak discharges of up to 200%, while the overestimation of time parameters beyond 800% could result in maximum peak discharge underestimations of up to 100%. Such errors in the estimation of time parameters could not only result in either the over- or under-design of hydraulic structures, but are also linked to several socio-economic implications and could result in infeasible projects. Consequently, catchment response time parameters are regarded as one of the primary inputs required when design floods need to be estimated, especially in ungauged catchments. The time of concentration (T_C), lag time (T_L) and time to peak (T_P) are the time parameters commonly used to express the catchment response time. T_C is the most frequently used and required time parameter in flood hydrology practice (Gericke & Smithers 2014) and continues to find application in both event-based methods (SANRAL 2013) and continuous hydrological (stormwater) models (USACE 2001; Neitsch *et al* 2005). Despite the widespread use of all these time parameters, unique working definitions for each of the parameters are not currently available. However, the use of several conceptual and computational time parameter definitions is proposed in the literature, as summarised by McCuen (2009), and Gericke and Smithers (2014), some of which are adopted in practice.

The simultaneous use of these different time parameter definitions, as proposed in literature, combined with the lack of continuously recorded rainfall data and available direct measurements of rainfall–runoff relationships, has curtailed the establishment of unbiased time parameter estimation procedures internationally (Grimaldi *et al* 2012). South Africa (SA) is no exception – none of the empirical T_C estimation equations recommended for general use have been tested, or developed and verified using local data. The South African National Roads Agency Limited (SANRAL 2013) recommends the use of the Kerby equation (Kerby 1959) developed for small, flat catchments with overland flow being dominant, but the Kerby equation is widely applied in an urban stormwater context in SA (e.g. roads, paved parking lots, business and industrial areas, residential lots, etc). Apart from the Kerby equation, the T_L equation of the United States Department of Agriculture, Soil Conservation Service (USDA SCS 1985), developed for catchment areas up to 30 km^2, is also sometimes used in SA to estimate overland flow T_C by recognising the relationship of $T_C : T_L$ = 1.417 (McCuen 2009). In applying the overland flow T_C equations, a practising engineer would typically use flow-length criteria, i.e. overland flow distances associated with specific slopes, as a limiting variable to quantify overland flow conditions (Matthee *et al* 1986; McCuen & Spiess 1995), but flow-retardant factors, Manning's overland roughness parameters and overland conveyance factors are also sometimes used (Viessman & Lewis 1996; Seybert 2006; USDA NRCS 2010).

In medium to large (50 km^2 to 35 000 km^2) catchments where channel flow dominates, the empirical United States Bureau of Reclamation (USBR) equation (USBR 1973) is the recommended equation in SA to estimate the T_C in a defined watercourse (SANRAL 2013). At these catchment levels, the current common practice used by engineers is to divide the principal flow path into overland flow (if significant, otherwise regarded as channel flow) and main watercourse or channel flow, after which the travel times in the various segments are computed separately and totalled. Gericke and Smithers (2014) demonstrated the inconsistency amongst various channel flow T_C equations applied at this catchment scale, along with their associated inherent limitations. It was argued that these equations would show even more significant variations if compared to observed catchment response times. Consequently, Gericke and Smithers (2014) proposed the use of an alternative and consistent approach to estimate T_C from observed streamflow data by recognising the approximation of the conceptual $T_C \approx T_P$ and assumption that the volume of effective rainfall equals the volume of direct runoff when a hydrograph is separated into direct runoff and baseflow. In using such an approach, the convolution process normally required between a single hyetograph and hydrograph to estimate T_C is eliminated, since only observed streamflow data is used without the need for rainfall data (Gericke & Smithers 2014). Acknowledging that the 'traditional' convolution process is not only impractical, but also not applicable in real, large heterogeneous catchments (where antecedent moisture from previous rainfall events and spatially non-uniform rainfall hyetographs can result in multi-peaked hydrographs), the conceptual and practical value of using such an alternative approach is recognised and warrants further investigation.

The objectives of the study reported in this paper are discussed in the next section, followed by a description of the case studies. Thereafter, the methodologies involved in meeting the objectives are detailed, followed by the results, discussion and conclusions.

PURPOSE OF STUDY

In this paper, selected definitions and associated estimation procedures are utilised for the analysis of three case studies with the two-fold objective of critically investigating the similarity between T_C and T_P at a medium to large catchment scale, and comparing different estimation methods. The latter comparison focuses on the use of direct estimation (from observed streamflow data in medium to large catchments) and indirect estimation (empirical equations) methodologies. The specific objectives of this paper are: (i) to compare a selection of overland flow T_C equations using different slope-distance classes and roughness parameter categories to highlight any inherent limitations and inconsistencies; (ii) to explicate the variability of T_C estimations resulting from the $T_C \approx T_P$ approach implemented on observed streamflow data at a medium to large catchment scale, and (iii) to ascertain the inherent limitations and inconsistencies of the empirical channel flow T_C equations when compared to the direct estimation of T_C from observed streamflow data.

The three case studies are presented in the next section.

CASE STUDIES

Three case studies were selected to benchmark the different equations commonly used internationally to estimate T_C in practice at different catchment scales, and to investigate their similarities, differences and limitations.

(a) Conceptual urban catchment

Urban catchments are normally characterised by highly variable and complex flow paths. Consequently, instead of using actual urban catchments, a conceptualised urban catchment setup, with overland flow being dominant, is selected by considering the combination of different variables, such as flow-length criteria (i.e. overland flow distances associated with specific slopes), overland conveyance factors (ϕ), flow-retardant/imperviousness factors (i_p),

Table 1 Overland flow distances associated with different slope classes (Matthee *et al* 1986)

Slope class (S_O) (%)	Distance (L_O) (m)
0–3	110
3.1–5	95
5.1–10	80
10.1–15	65
15.1–20	50
20.1–25	35
25.1–30	20

Manning's overland roughness parameters (n) and runoff curve numbers (CN). The flow-length criteria are based on the recommendations made in the National Soil Conservation Manual (NSCM) (Matthee *et al* 1986). The NSCM criteria (Table 1) are based on the assumption that the steeper the overland slope, the shorter the length of actual overland flow before it transitions into shallow-concentrated flow, followed by channel flow. A total of five categories defined by different ϕ, i_p, n and CN values in seven slope-distance classes are considered.

(b) Central Interior (summer rainfall)

Six catchment areas, ranging from 39 km^2 to 33 278 km^2 situated in the C5 secondary drainage region (Midgley *et al* 1994), were selected as case study areas in this climatological region predominantly characterised by convective rainfall during the summer months. The mean annual precipitation (MAP) ranges from 428 mm to 654 mm (Lynch 2004). The topography is gentle, with elevations varying from 1 021 m to 2 120 m, and with average catchment slopes ranging between 1.7% and 10.3% (USGS 2002). A total of 450 observed flood events from 1931 to 2013 are included in the analysis.

(c) South Western Coastal region (winter rainfall)

Six catchment areas, ranging from 47 km^2 to 2 878 km^2 situated in the G1, H1, H4 and H6 secondary drainage regions (Midgley *et al* 1994), were selected as case study areas in this climatological region predominantly characterised by winter rainfall. The MAP ranges from 450 mm to 915 mm (Lynch 2004), and rainfall is classified as either orographic and/or frontal rainfall. The topography is very steep, with elevations varying from 86 m to 2 240 m, and with average catchment slopes ranging between 25.6% and 41.6% (USGS 2002). A total of 460 observed flood events from 1932 to 2013 are included in the analysis.

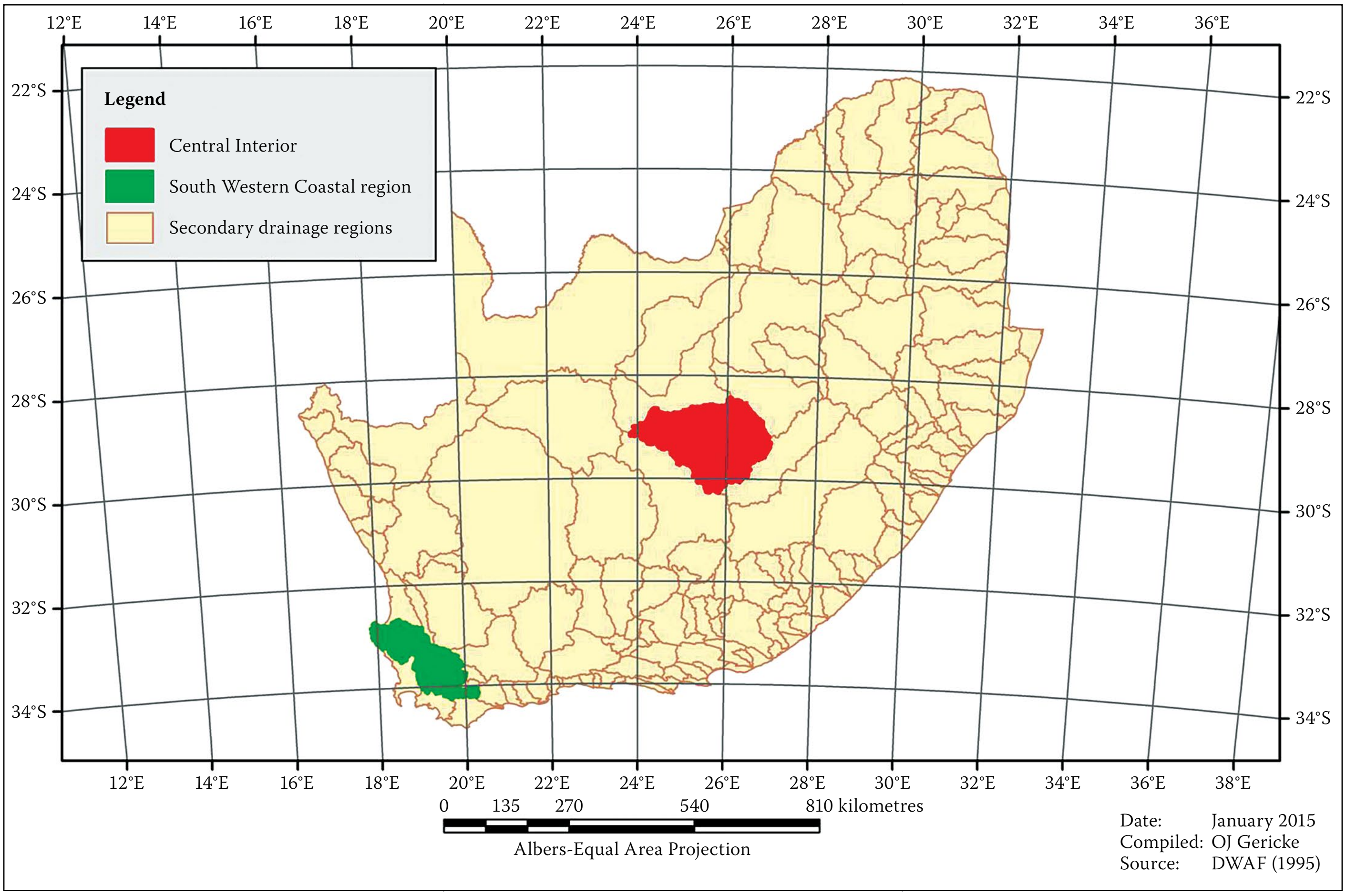

Figure 1 Location of case study areas (b) and (c)

The locations of the case study areas as listed in (b) and (c) are shown in Figure 1. Table 2 contains a summary of the main morphometric properties for each catchment under consideration.

The influences of each variable or parameter listed in Table 2 are highlighted where applicable in the subsequent sections. The next section includes the detailed methodology followed during this study, focusing on the indirect estimation (empirical equations) and direct estimation (from observed streamflow data) of T_C.

METHODOLOGY: TIME OF CONCENTRATION ESTIMATION PROCEDURES

In order to evaluate and compare the consistency of a selection of time parameter estimation methods in case study areas (a) to (c), the following steps were followed: (i) application and comparison of six overland flow T_C equations to the Kerby equation (Equation 2) in different slope-distance classes and roughness parameter categories; (ii) direct estimation of T_C from observed streamflow data based on the $T_C \approx T_P$ approach; and (iii) application of six channel flow T_C equations in 12 medium to large catchments in order to compare their results with the results as obtained in (ii).

Table 2 Main morphometric properties of catchments in the Central Interior and South Western Coastal region

Central Interior (summer rainfall)						
Catchment descriptor	**C5H008**	**C5H012**	**C5H015**	**C5H016**	**C5H022**	**C5H035**
Area (A) (km^2)	598	2 366	5 939	33 278	39	17 359
Minimum elevation (m)	1 397	1 322	1 254	1 021	1 531	1 104
Maximum elevation (m)	1 740	1 780	2 120	2 120	2 060	2 120
Average catchment slope (S) (m/m)	0.0483	0.0328	0.0277	0.0209	0.1029	0.0173
Hydraulic length (L_H) (km)	41.0	86.9	160.5	378.1	8.0	373.3
Centroid distance (L_C) (km)	22.4	45.3	81.0	230.2	2.7	172.7
Main river / watercourse length (L_{CH}) (km)	40.9	86.7	160.2	377.9	7.9	373.0
Average main river slope (S_{CH}) (m/m)	0.0049	0.0027	0.0014	0.0010	0.0170	0.0008
South Western Coastal region (winter rainfall)						
Catchment descriptor	**G1H003**	**G1H007**	**H1H007**	**H1H018**	**H4H006**	**H6H003**
Area (A) (km^2)	47	724	80	109	2 878	500
Minimum elevation (m)	199	86	273	375	185	297
Maximum elevation (m)	1 400	1 780	1 700	1 960	2 240	1 660
Average catchment slope (S) (m/m)	0.2889	0.2621	0.4069	0.4161	0.2921	0.2556
Hydraulic length (L_H) (km)	9.7	55.5	19.0	22.8	109.9	38.6
Centroid distance (L_C) (km)	5.0	29.0	9.5	9.3	26.9	13.6
Main river / watercourse length (L_{CH}) (km)	9.2	55.3	18.9	22.8	101.5	38.2
Average main river slope (S_{CH}) (m/m)	0.0177	0.0046	0.0333	0.0320	0.0047	0.0098

The details of the empirical equations as used in (i) and (iii) are listed and discussed first, followed by a description of the procedures followed in (ii).

Indirect estimation using empirical equations

The empirical equations selected require a limited amount of information and similar input variables to estimate T_C in ungauged catchments, as proposed by Williams (1922), Kirpich (1940), Johnstone and Cross (1949), Miller (1951), Kerby (1959), Reich (1962), Espey and Winslow (1968), FAA (1970), USBR (1973), Sheridan (1994), and (Sabol 2008). The empirical equations are detailed in the next two sub-sections for overland flow and channel flow regimes. All the equations are presented in Système International d'Unités (SI Units).

Overland flow regime

The empirical overland flow T_C equations are applied within the 'conceptual urban catchment' (Case study (a)) by considering the seven different NSCM slope-distance classes and five categories with associated flow conveyance (ϕ), retardant (imperviousness i_p), Manning's roughness (n) and runoff curve number (CN) variables. The five different ϕ categories are based on the work done by Viessman and Lewis (1996), with typical ϕ values ranging from 0.6 (i_p = 80%; n = 0.02; CN = 95); 0.8 (i_p = 50%; n = 0.06; CN = 85); 1.0 (i_p = 30%; n = 0.09; CN = 75); 1.2 (i_p = 20%; n = 0.13; CN = 72) to 1.3 (i_p = 10%; n = 0.15; CN = 70).

The six overland flow T_C equations are summarised in Equations 1 to 6.

a. **Miller (1951):** Equation 1 is based on a nomograph for shallow sheet overland flow as published by the Institution of Engineers, Australia (Miller 1951; IEA 1977; ADNRW 2007).

$$T_{C1} = 107\left[\frac{nL_O^{0.333}}{(100S_O)^{0.2}}\right] \tag{1}$$

where
T_{C1} = overland time of concentration (minutes),
L_O = length of overland flow path (m),
n = Manning's roughness parameter for overland flow, and
S_O = average overland slope (m/m).

b. **Kerby (1959):** Equation 2 is commonly used to estimate the T_C both as mixed-sheet and/or shallow-concentrated overland flow in the upper reaches of small, flat catchments. The Drainage Manual (SANRAL 2013) also recommends the use thereof in SA. McCuen *et al* (1984) highlighted that Equation 2 was developed and calibrated for catchments in the United States of America (USA) for areas less than 4 ha, with average slopes of less than 1% and Manning's roughness parameters (n) varying between 0.02 and 0.8.

$$T_{C2} = 1.4394\left(\frac{nL_O}{\sqrt{S_O}}\right)^{0.467} \tag{2}$$

where
T_{C2} = overland time of concentration (minutes),
L_O = length of overland flow path (m),
n = Manning's roughness parameter for overland flow, and
S_O = average overland slope (m/m).

c. **SCS (1962):** Equation 3 is commonly used to estimate the T_C as mixed-sheet and/or concentrated overland flow in the upper reaches of a catchment. The USDA SCS developed this equation in 1962 (Reich 1962) for homogeneous, agricultural catchment areas up to 8 km^2 with mixed overland flow conditions dominating (USDA SCS 1985).

$$T_{C3} = \frac{L_O^{0.8}\left[\dfrac{25\,400}{CN} - 228.6\right]^{0.7}}{706.9S_O^{0.5}} \tag{3}$$

where
T_{C3} = overland time of concentration (minutes),
CN = runoff curve number,
L_O = length of overland flow path (m), and
S_O = average overland slope (m/m).

d. **Espey-Winslow (1968):** Equation 4 was developed using data from 17 catchments in Houston, USA, with areas ranging from 2.6 km^2 to 90.7 km^2. The imperviousness factor (i_p) represents overland flow retardant, while the conveyance factor (ϕ) measures subjectively the hydraulic efficiency of a flow path, taking both the condition of the surface cover and degree of development into consideration (Espey & Winslow 1968).

$$T_{C4} = 44.1\left[\frac{\phi L_O^{0.29}}{S_O^{0.145}i_p^{0.6}}\right] \tag{4}$$

where
T_{C4} = overland time of concentration (minutes),
i_p = imperviousness factor (%),
ϕ = conveyance factor,
L_O = length of overland flow path (m), and
S_O = average overland slope (m/m).

e. **Federal Aviation Agency (FAA 1970):** Equation 5 is commonly used in urban overland flow estimations, since the Rational method's runoff coefficient (C) is included (FAA 1970; McCuen *et al* 1984).

$$T_{C5} = \frac{1.8(1.344 - C)L_O^{0.5}}{(100S_O)^{0.333}} \tag{5}$$

where
T_{C5} = overland time of concentration (minutes),
C = Rational method runoff coefficient (≈ default i_p fraction values),
L_O = length of overland flow path (m), and
S_O = average overland slope (m/m).

f. **NRCS kinematic wave (1986):** Equation 6 was originally developed by Welle and Woodward (1986) to avoid the iterative use of the original kinematic wave equation (Morgali & Linsley 1965) and is based on a power–law relationship between design rainfall intensity and duration.

$$T_{C6} = \frac{5.476}{P_2^{0.5}}\left(\frac{nL_O}{\sqrt{S_O}}\right)^{0.8} \tag{6}$$

where
T_{C6} = overland time of concentration (minutes),
L_O = length of overland flow path (m),
n = Manning's roughness parameter for overland flow,
P_2 = two-year return period 24-hour design rainfall depth (mm, default = 100), and
S_O = average overland slope (m/m).

Channel flow regime

In the medium to large catchments located in case study areas (b) and (c), channel flow in the main watercourses is assumed to dominate. Consequently, a selection of six channel flow T_C equations with similar input variables are applied and compared to the direct T_C estimation results (referred to as T_{Cx} in this paper) obtained from observed streamflow data using the assumption of the conceptual $T_C \approx T_P$.

The six channel flow T_C equations are summarised in Equations 7 to 12.

g. **Bransby-Williams (1922):** The use of Equation 7 (Williams 1922) is limited to rural catchment areas less than ± 130 km^2 (Fang *et al* 2005; Li & Chibber 2008). The Australian Department of Natural

Resources and Water (ADNRW 2007) highlighted that the initial overland flow travel time is already incorporated, therefore an overland flow or standard inlet time should not be added.

$$T_{C7} = 0.2426\left(\frac{L_{CH}}{A^{0.1}S_{CH}{}^{0.2}}\right) \quad (7)$$

where
T_{C7} = channel flow time of concentration (hours),
A = catchment area (km^2),
L_{CH} = length of longest watercourse (km), and
S_{CH} = average main watercourse slope (m/m, using the 10-85 method).

h. **Kirpich (1940):** Equation 8 was calibrated in small, agricultural catchments (< 45 ha) located in the USA with average catchment slopes ranging between 3% and 10%. McCuen *et al* (1984) showed that Equation 8 had a tendency to underestimate T_C values in 75% of urbanised catchments with areas smaller than 8 km^2, while in 25% of the catchments (8 km^2 < A ≤ 16 km^2) with substantial channel flow, it had the smallest bias when compared to the observed T_{Cx} values.

$$T_{C8} = 0.0663\left(\frac{L_{CH}{}^2}{S_{CH}}\right)^{0.385} \quad (8)$$

where
T_{C8} = channel flow time of concentration (hours),
L_{CH} = length of longest watercourse (km), and
S_{CH} = average main watercourse slope (m/m, using the 10-85 method).

i. **Johnstone-Cross (1949):** Equation 9 was developed to estimate T_C in the Scioto and Sandusky River catchments (Ohio Basin) with areas ranging from 65 km^2 to 4 206 km^2 (Johnstone & Cross 1949; Fang *et al* 2008).

$$T_{C9} = 0.0543\left(\frac{L_{CH}}{S_{CH}}\right)^{0.5} \quad (9)$$

where
T_{C9} = channel flow time of concentration (hours),
L_{CH} = length of longest watercourse (km), and
S_{CH} = average main watercourse slope (m/m, using the 10-85 method).

j. **USBR (1973):** Equation 10 was proposed by the USBR (1973) to be used as a standard empirical equation to estimate the T_C in hydrological designs, especially culvert designs based on the California Culvert Practice (CCP 1955, cited by Li & Chibber 2008). However, in essence it is a modified version of Equation 8 as proposed by Kirpich (1940) and is recommended by SANRAL (2013) for general use in SA.

$$T_{C10} = \left(\frac{0.87\,L_{CH}{}^2}{1000\,S_{CH}}\right)^{0.385} \quad (10)$$

where
T_{C10} = channel flow time of concentration (hours),
L_{CH} = length of longest watercourse (km), and
S_{CH} = average main watercourse slope (m/m, using the 10-85 method).

k. **Sheridan (1994):** Equation 11 was developed to estimate the T_C using data from nine catchments in Georgia and Florida, USA, with catchment areas ranging between 2.6 km^2 and 334.4 km^2 (Sheridan 1994; USDA NRCS 2010).

$$T_{C11} = 2.2L_{CH}{}^{0.92} \quad (11)$$

where
T_{C11} = channel flow time of concentration (hours), and
L_{CH} = length of longest watercourse (km).

l. **Colorado-Sabol (2008):** Sabol (2008) proposed three different empirical T_C equations to be used in catchments with distinctive geomorphological and land-use characteristics in the State of Colorado, USA. Equation 12 is the equation applicable to rural catchments.

$$T_{C12} = 0.9293\left[\frac{A^{0.1}(L_{CH}L_C)^{0.25}}{S_{CH}{}^{0.2}}\right] \quad (12)$$

where
T_{C12} = channel flow time of concentration (hours),
A = catchment area (km^2),
L_C = centroid distance (km),
L_{CH} = length of longest watercourse (km), and
S_{CH} = average main watercourse slope (m/m, using the 10-85 method).

The direct estimation of T_{Cx} from observed streamflow data is discussed in the next section.

Direct estimation from observed streamflow data

The procedure as proposed by Gericke and Smithers (2014) and implemented by them (Gericke & Smithers 2015) is used to estimate T_{Cx} directly from observed streamflow data. In summary, the following steps were followed and also implemented in this study:

Establishment of flood database

Department of Water and Sanitation (DWS) primary flow data consisting of an up-to-date sample (DWS 2013) of the 12 continuous flow-gauging stations located at the outlet of each catchment in the Central Interior and South Western Coastal region was prepared and evaluated using the screening process as proposed by Gericke and Smithers (2015). The screening process accounts for: (i) streamflow record lengths (> 30 years), (ii) representative catchment area ranges (30 < A ≤ 35 000 km^2), and (iii) representative rating tables, i.e. extrapolation of rating tables was limited to 20% in cases where the observed river stage exceeded the maximum rated levels (H). Gericke and Smithers (2015) used third-order polynomial regression analyses to extrapolate the rating tables. Hydrograph shape (especially the peakedness as a result of a steep rising limb, in relation to the hydrograph base length) and the relationship between observed peak discharge (Q_{Pxi}) and direct runoff volume (Q_{Di}) pair values were used as additional criteria to justify the individual stage extrapolations (H_E) up to a 20% limit, i.e. $H_E \leq 1.2\,H$. Typically, in such an event, the increase in Q_{Di} due to the extrapolation was limited to 5%, hence the error made by using larger direct runoff volumes had little impact on the sample statistics of the total flood volume. This approach was justified in having samples of reasonable size (a total of 1 134 flood hydrographs in the C5 secondary drainage region), while the primary focus was on the time when the peak discharge occurs, not necessarily just the magnitude thereof. It is also important to note that Görgens (2007) also used a 20% stage limit to extrapolate rating tables as used in the development of the Joint Peak-Volume (JPV) method.

Extraction of flood hydrographs

Complete flood hydrographs were extracted using selection criteria as proposed by Gericke and Smithers (2015), and are based on: (i) the implementation of truncation levels (i.e. only flood events > smallest annual maximum flood event were extracted), and (ii) the identification of mutual start/end times on both the flood hydrographs and baseflow curves, hence ensuring that when a hydrograph is separated into direct runoff and baseflow, the identified separation point represents the start of direct runoff which coincides with the onset of effective rainfall. The end of a flood event was also determined using a recursive filtering method (Nathan & McMahon 1990).

Analyses of flood hydrographs

The direct runoff and baseflow were separated using the recursive digital filtering method (Equation 13) as initially proposed by Nathan and McMahon (1990) and adopted by Smakhtin and Watkins (1997) in a national-scale study in SA.

$$Q_{Di} = \alpha Q_{D(i-1)} + \beta(1+\alpha)(Q_{Ti} - Q_{T(i-1)}) \quad (13)$$

where

Q_{Di} = filtered direct runoff at time step i, which is subject to $Q_D \geq 0$ for time i (m^3/s),

α, β = filter parameters, and

Q_{Ti} = total streamflow (i.e. direct runoff plus baseflow) at time step i (m^3/s).

The application of Equation 13 using a fixed α-parameter of 0.995 (Smakhtin & Watkins 1997) and a fixed β-parameter of 0.5 (Hughes *et al* 2003) resulted in the estimation of the following hydrograph parameters: (i) start/end date/time of flood hydrograph, (ii) observed peak discharge (Q_{Pxi}, m^3/s), (iii) total volume of runoff (Q_{Ti}, m^3), (iv) volume of direct runoff (Q_{Di}, m^3), (v) volume of baseflow (Q_{Bi}, m^3), (vi) baseflow index (BFI, which equals the ratio of Q_{Bi}/Q_{Ti}), (vii) depth of effective rainfall (P_{Ei}, mm, based on the assumption that the volume of direct runoff equals the volume of effective rainfall and that the total catchment area is contributing to runoff), and (viii) time to peak (T_{Pxi}, hours).

Lastly, the analysed flood hydrographs were subjected to a final filtering process (Gericke & Smithers 2015) to ensure that all the flood hydrographs are independent and that the conceptual T_{Cxi} values are consistent, i.e. the likelihood of higher Q_{Pxi} values to be associated with larger Q_{Di} and T_{Cxi} values, while taking cognisance of their dependence on factors such as antecedent moisture conditions and non-uniformities in the temporal and spatial distribution of storm rainfall. Furthermore, the use of 'truncation levels', i.e. when only flood events larger than the smallest annual maximum flood event on record are extracted, ensured that 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. It is important to note that Gericke and Smithers (2014; 2015) defined the T_{Cxi} values as shown in Equation 14.

$$T_{Cxi} = \sum_{j=1}^{N} t_j \quad (14)$$

Table 3 Consistency measures for the testing of overland flow T_C estimation equations compared to Equation 2 (Kerby 1959)

Equations	Consistency measures					
	Mean estimated T_C (Eq 2) (min)	Mean estimated T_C (min)	Standard bias statistic (Eq 16) (%)	Mean error (min)	Maximum error (min)	Standard error (min)
Miller (Eq 1)	5.3	23.8	327.3	18.5	49.5	1.1
SCS (Eq 3)	5.3	3.4	–44.6	–1.9	–3.3	0.8
Espey-Winslow (Eq 4)	5.3	31.1	469.2	25.8	81.5	1.8
FAA (Eq 5)	5.3	6.6	20.3	1.3	4.2	0.4
NRCS (Eq 6)	5.3	6.0	–6.2	0.6	8.9	0.5

where

T_{Cxi} = conceptual time of concentration which equals the observed T_{Pxi} for each individual flood event (hours),

t_j = duration of the total net rise (excluding the in-between recession limbs) of a multiple-peaked hydrograph (hours), and

N = sample size.

The mean of the individual flood events in each catchment calculated using Equation 14 could be used as the actual catchment response time. However, Gericke and Smithers (2015) highlighted that the use of such averages could be misleading and might not be a good reflection of the actual response time. Therefore, by considering the high variability of catchment responses calculated for each event as evident in the results from this study, as well as taking cognisance of the procedure adopted by Gericke and Smithers (2015), the use of a 'representative average value' equal to the linear catchment response function of Equation 15 (Gericke & Smithers 2015) was used to confirm the

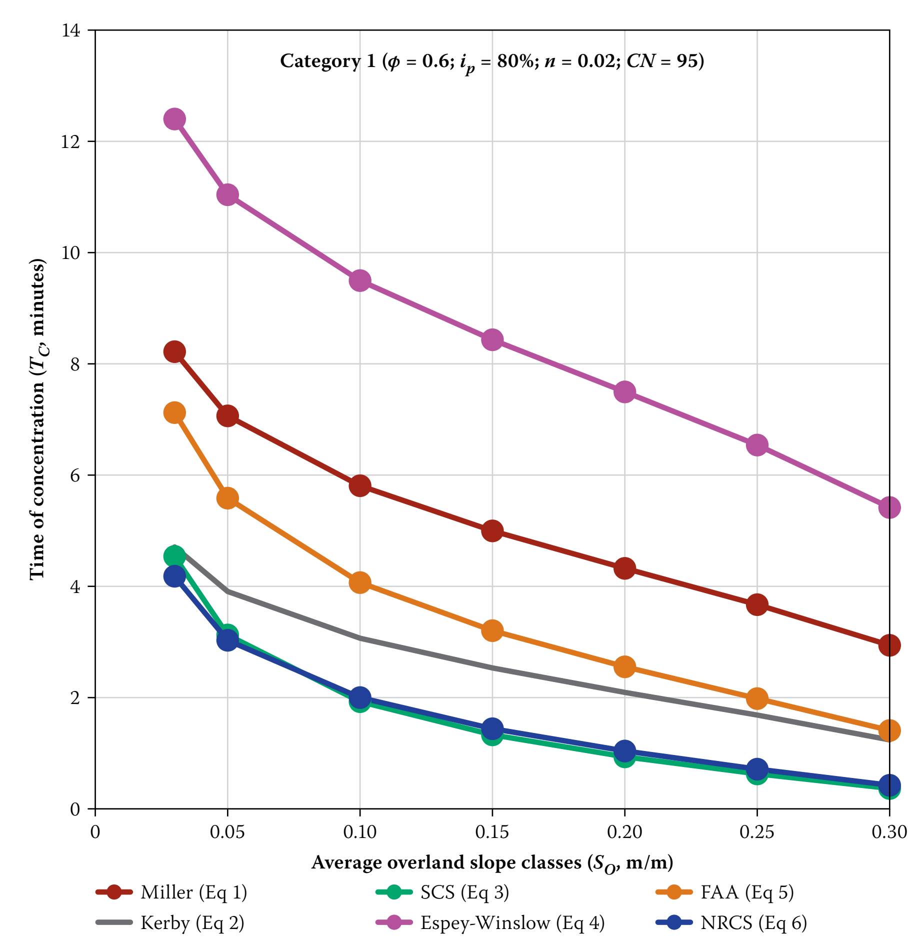

Figure 2(a) Category 1: Variation of overland flow T_C estimates in different average overland slope classes validity and representativeness of the mean of the values calculated from each event.

$$T_{C\,linear} = \frac{1}{3\,600}\left[\frac{\sum_{i=1}^{N}(Q_{Pxi} - \overline{Q_{Px}})(Q_{Di} - \overline{Q_D})}{\sum_{i=1}^{N}(Q_{Pxi} - \overline{Q_{Px}})^2}\right] \quad (15)$$

where

$T_{C\,linear}$ = conceptual T_C assuming a linear catchment response (hours),

Q_{Di} = volume of direct runoff for individual events (m^3),

$\overline{Q_D}$ = mean of Q_{Di} (m^3),

Q_{Pxi} = observed peak discharge for individual events (m^3/s),

$\overline{Q_{Px}}$ = mean of Q_{Pxi} (m^3/s), and

N = sample size.

In each catchment, the results based on Equations 14 and 15 were compared to establish their degree of association. Despite the high degree of association evident, Equation 15 was regarded as the most consistent procedure to estimate the most representative catchment T_{Cx} values. The preferential use of Equation 15 is motivated by the fact that the hydrograph analysis tool (HAT) developed by Gericke and Smithers (2015) could not always, due to the nature of flood hydrographs, cater for the different variations in flood hydrographs, especially when Equation 14 was applied. Therefore, a measure of user intervention is sometimes required, and consequently it could be argued that some inherent inconsistencies could possibly have been introduced. Taking cognisance of the latter possibility, the use of Equation 15 is therefore regarded as being more objective and with consistent results.

A standardised bias statistic (Equation 16) (McCuen *et al* 1984) was used with the mean error (difference in the average of the observed and estimated values in different classes/categories/catchments) as a measure of actual bias and to ensure that the T_C estimation results are not dominated by errors in the large T_C values. The standard error of the estimate was also used to provide another measure of consistency.

$$B_S = 100\left[\frac{1}{z}\sum_{i=1}^{z}\frac{|T_{Cyi} - T_{Cxi}|}{T_{Cxi}}\right] \quad (16)$$

where

B_S = standardised bias statistic (%),

T_{Cxi} = observed time of concentration (minutes or hours),

T_{Cyi} = estimated time of concentration (minutes or hours), and

z = number of slope-distance categories (overland flow regime) or sub-catchments (channel flow regime).

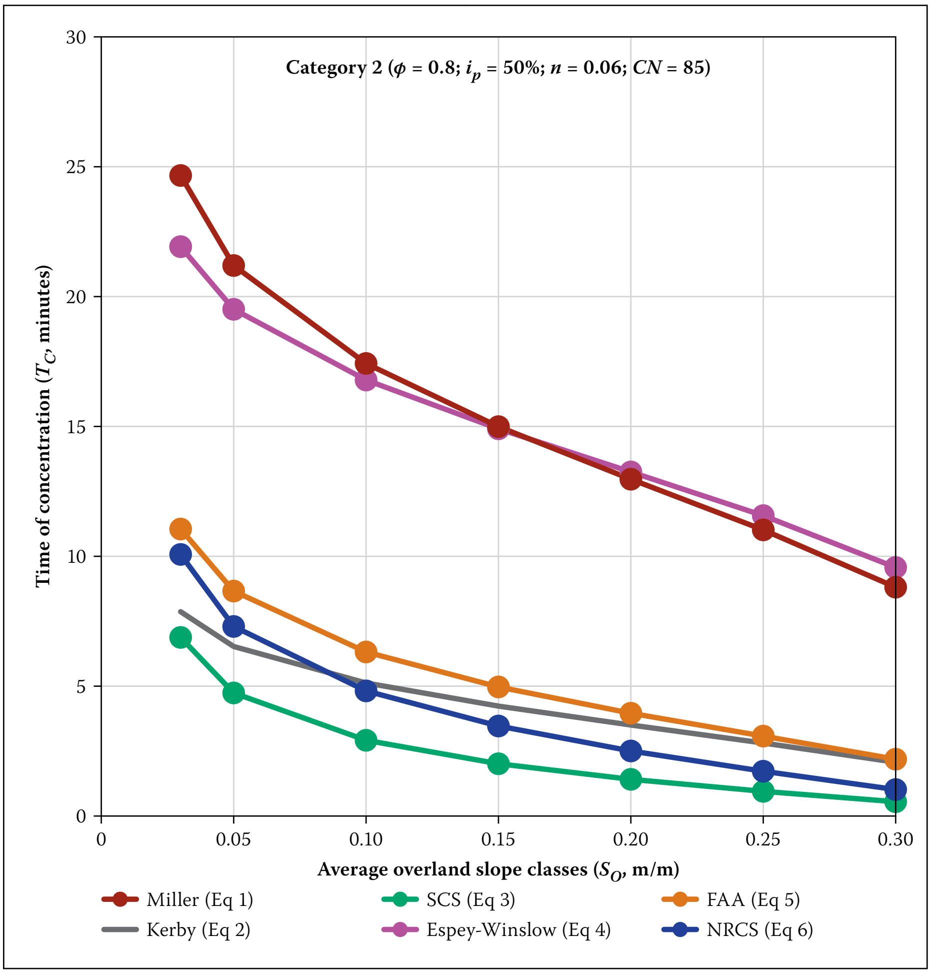

Figure 2(b) Category 2: Variation of overland flow T_C estimates in different average overland slope classes

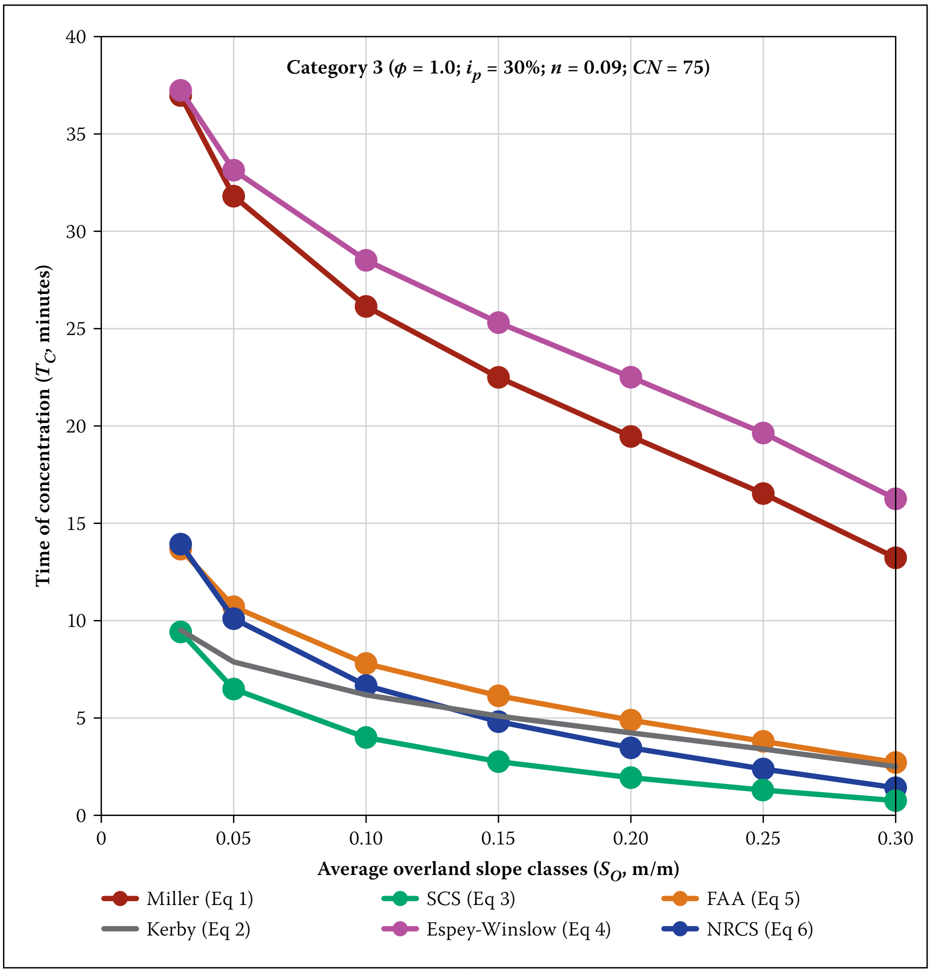

Figure 2(c) Category 3: Variation of overland flow T_C estimates in different average overland slope classes

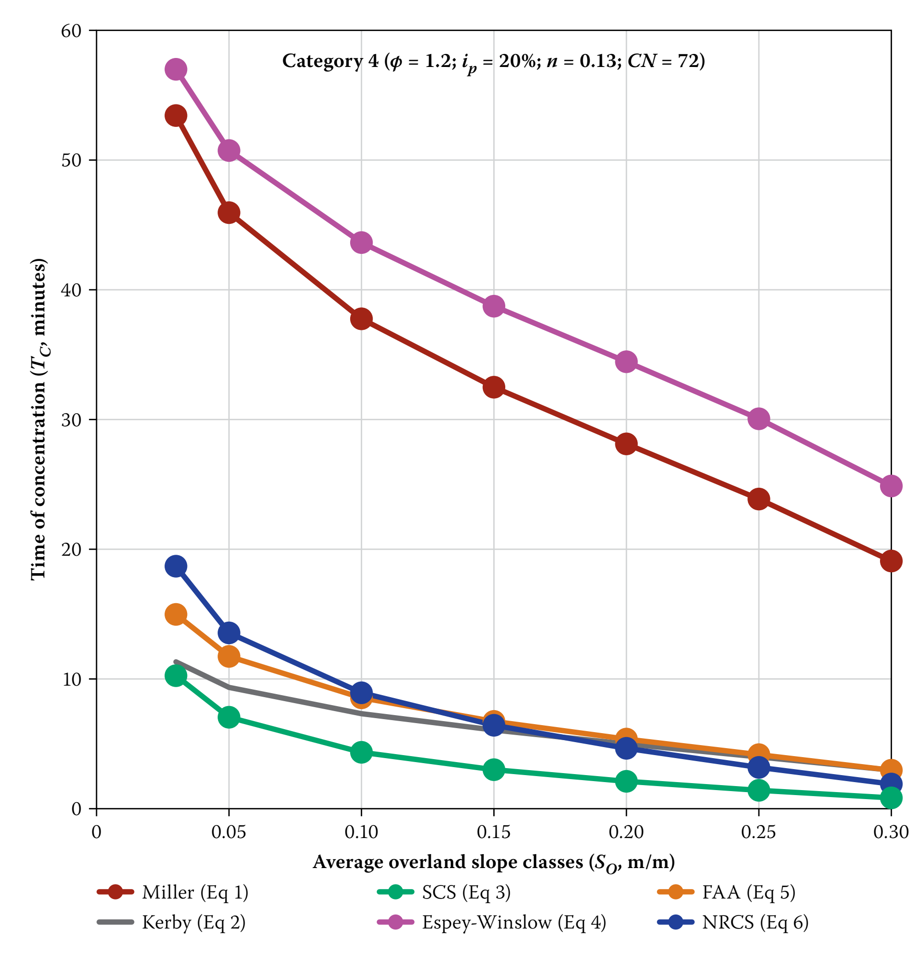

Figure 2(d) Category 4: Variation of overland flow T_C estimates in different average overland slope classes

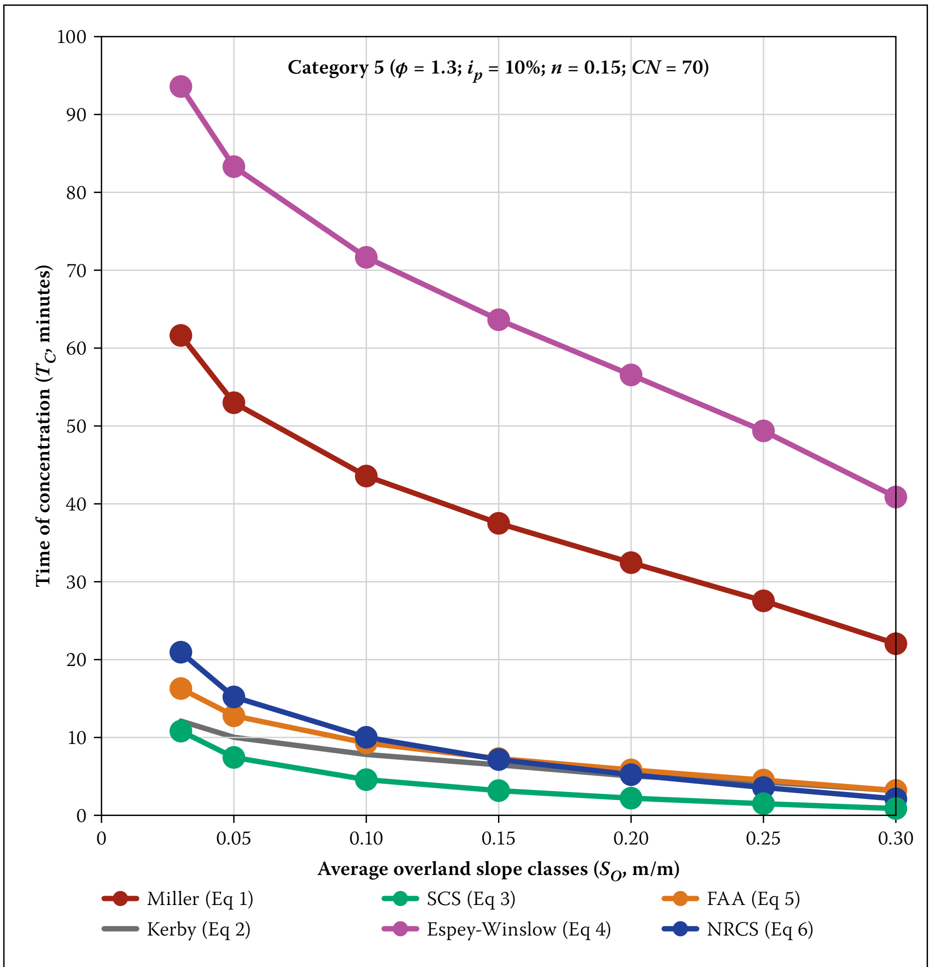

Figure 2(e) Category 5: Variation of overland flow T_C estimates in different average overland slope classes

RESULTS AND DISCUSSION

The results from the application of the above methodology using different T_C estimation procedures as applied in case study areas (a) to (c) are presented in this section. The station numbers of the DWS flow-gauging stations located at the outlet of each catchment are used as the catchment descriptors for easy reference in all the tables and figures.

Indirect T_C estimation results (overland flow regime)

The results from the estimated overland flow T_C for the seven different NSCM slope-distance classes and five categories are shown in Figures 2(a) to 2(e).

From the results contained in Figures 2(a) to 2(e), the five equations (Equations 1 and 3 to 6) used to estimate the overland flow T_C in case study area (a), relative (not absolute) to the T_C estimated using the Kerby equation (Equation 2), showed different biases when compared in each of the five different flow-retardant categories and associated slope-distance classes. As expected, all the T_C estimates decreased with an increase in the average overland slope, while T_C gradually increases with an increase in the surface roughness and permeability. The SCS equation (Equation 3) constantly underestimated T_C, while the Miller (Equation 1) and Espey-Winslow (Equation 4) equations overestimated T_C in all cases when compared to the estimates based on the Kerby equation (Equation 2). The NRCS kinematic wave equation (Equation 6) underestimated T_C in relation to the Kerby equation (Equation 2) in Category 1, while other T_C underestimations were witnessed in Categories 2 (S_O ≥ 0.10 m/m), 3 (S_O ≥ 0.15 m/m), and 4 to 5 (S_O ≥ 0.20 m/m). The poorest results in relation to the Kerby equation (Equation 2) were obtained using the Espey-Winslow equation (Equation 4) and could be ascribed to the use of default conveyance (ϕ) factors which might not be representative, since this is the only equation using ϕ as a primary input parameter.

In considering the overall average consistency measures compared to the Kerby equation (Equation 2) as listed in Table 3, the NRCS kinematic wave equation (Equation 6) provided relatively the smallest bias (< 10%), with a mean error ≤ 1 minute. Both the standardised bias (469.2%) and mean error (26 minutes) of the Espey-Winslow equation (Equation 4) were large compared to the other equations. The SCS equation (Equation 3) resulted in the smallest maximum absolute error of 3.3 minutes, while the Espey-Winslow equation (Equation 4) had a maximum absolute

Table 4 Summary of average hydrograph parameters for different catchments in the Central Interior and South Western Coastal region

Central Interior (summer rainfall)									
Catchment descriptor	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_{Cx} (Eq 14) (hrs)	$T_{C\ linear}$ (Eq 15) (hrs)	P_E (mm)	BFI
C5H008	1931/04/01 to 1986/04/01	112	2.2	2.0	44.7	8.0	10.5	3.3	0.1
C5H012	1936/04/01 to 2013/02/13	68	3.3	2.3	41.5	11.9	11.9	1.0	0.3
C5H015	1949/01/01 to 1983/11/22	90	23.3	21.0	203.1	26.7	25.0	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
C5H022	1980/10/14 to 2013/10/24	70	0.37	0.31	11.5	5.3	6.1	8.0	0.2
C5H035	1989/08/03 to 2013/07/23	70	19.4	16.6	91.8	38.8	41.0	1.0	0.1
South Western Coastal region (winter rainfall)									
Catchment descriptor	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_{Cx} (Eq 14) (hrs)	$T_{C\ linear}$ (Eq 15) (hrs)	P_E (mm)	BFI
G1H003	1949/03/21 to 2013/08/27	75	1.6	1.2	20.6	8.3	9.2	24.4	0.2
G1H007	1951/04/02 to 1977/05/31	75	50.4	43.9	238.9	36.0	37.1	60.7	0.1
H1H007	1950/04/10 to 2013/07/25	98	10.5	7.6	196.8	10.3	10.3	95.0	0.3
H1H018	1969/02/26 to 2013/07/26	80	15.0	11.0	323.3	11.1	10.9	100.9	0.3
H4H006	1950/04/19 to 1990/08/06	80	105.7	78.9	453.5	43.9	44.8	27.4	0.2
H6H003	1932/10/01 to 1974/11/11	52	16.9	13.2	58.1	31.5	32.1	26.3	0.2

error of 82 minutes. The standard deviation of the errors provides another measure of correlation, with standard errors < 1 minute (Equations 3, 5 and 6).

Direct T_C estimation results

Only 5.6% and 6.9% of the total number of flood hydrographs analysed in the Central Interior and South Western Coastal regions respectively were subjected to the extrapolation of stage values (H_E) above the maximum rated levels (H) within the range $H_E \leq 1.2\ H$ and $Q_{Di} \leq 5\%$. Thus, the error made by using larger direct runoff volumes had little impact on the sample statistics of the total flood volume, especially if the total sample size of the analysed flood hydrographs is taken into consideration. It is important to note, as highlighted before, that the primary focus is on the time when the peak discharge occurs, not necessarily just the magnitude thereof.

The averaged hydrograph parameters computed using Equation 13 with $\alpha = 0.995$ and $\beta = 0.5$ applied to the extracted observed hydrograph data are listed in Table 4. Figures 3 (Central Interior) and 4 (South Western Coastal region) show the regional observed peak discharge (Q_{Pxi}) versus the conceptual T_{Cxi} ($\approx T_{Pxi}$) values for all the catchments under consideration.

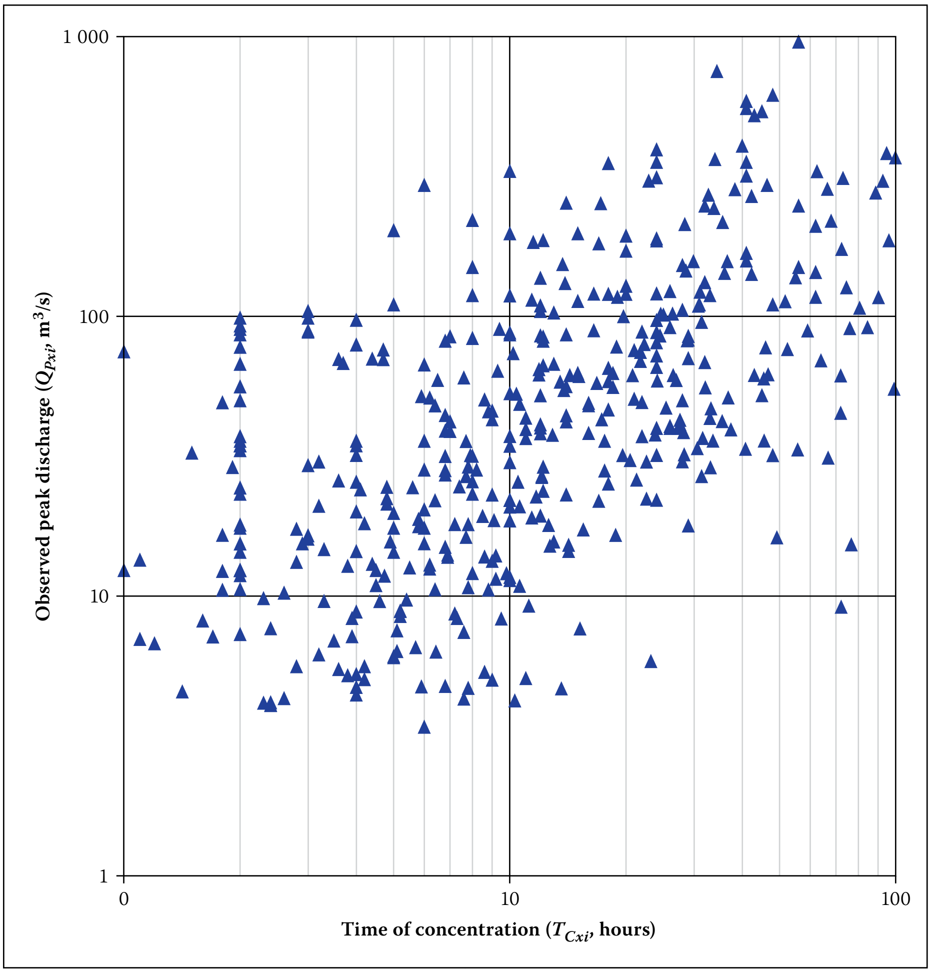

Figure 3 Regional Q_{Pxi} versus conceptual T_{Cxi} values (Central Interior)

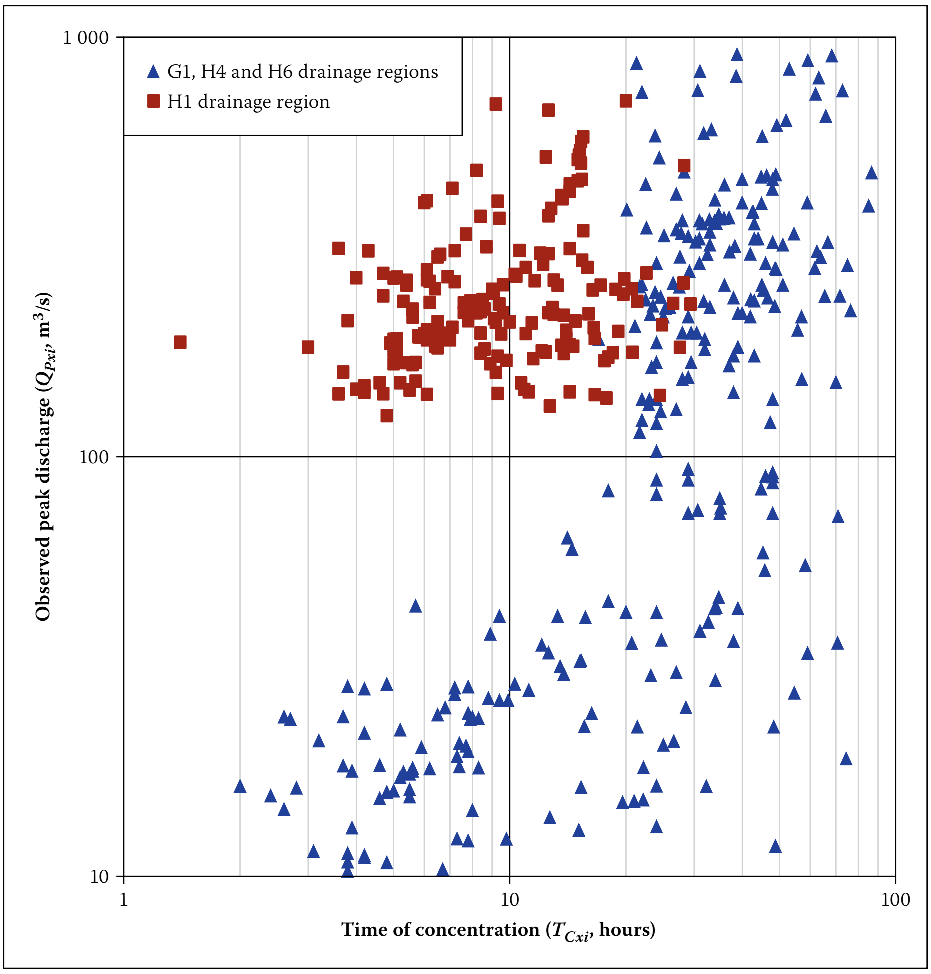

Figure 4 Regional Q_{Pxi} versus conceptual T_{Cxi} values (South Western Coastal region)

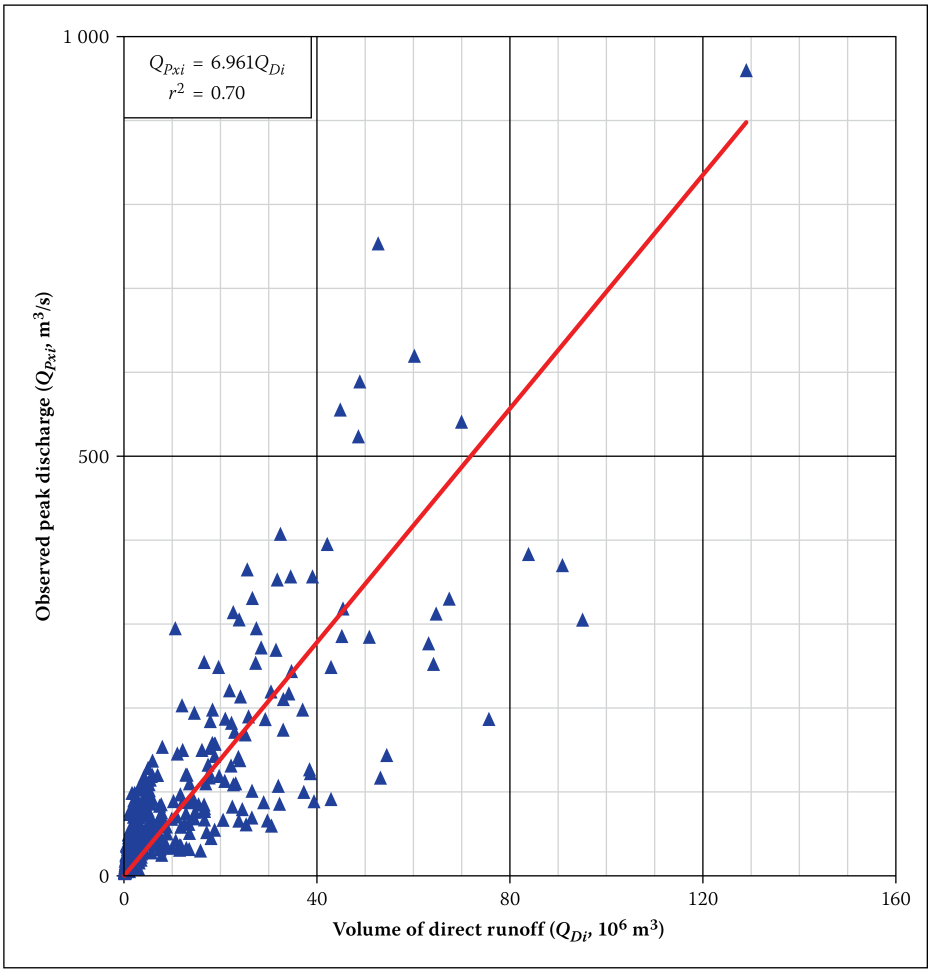

Figure 5 Direct estimation of T_{Cx} (Eq 15) from observed streamflow data (Central Interior)

The data scatter in these figures demonstrates the inherent variability of Q_{Pxi} and T_{Cxi} in medium to large catchments at a regional level. It is evident that the direct T_{Cxi} estimations from the observed streamflow data (Equation 14) could vary significantly, with the largest Q_{Pxi} and T_{Cxi} values associated with the likelihood of the entire catchment receiving rainfall for the critical storm duration. Smaller T_{Cxi} values could be expected when effective rainfall of high average intensity does not cover the entire catchment, especially when a storm is centred near the outlet of a catchment. The regional T_{Cxi} values in Figure 3 show a stronger linear correlation (r^2 = 0.70) when compared to the regional T_{Cxi} values (r^2 = 0.40) in Figure 4. The latter stronger linear correlation shown in Figure 3 confirms that more homogeneous catchment responses were obtained in the Central Interior than in the South Western Coastal region (Figure 4). However, in Figure 4, the regional T_{Cxi} values consist of two 'different populations', i.e. the T_{Cxi} in relation to Q_{Pxi} and the catchment area varies from catchment to catchment. This could be ascribed to differences in their morphometric properties, as well as to the spatial location of these catchments in different secondary drainage regions. The catchment responses in the H1 secondary drainage region differ from those catchments situated in the G1, H4 and H6 secondary drainage regions, with the Q_{Pxi} values generally larger for corresponding or shorter T_{Cxi} values, while the catchment areas are also smaller. Apart from the smaller catchment areas, the average catchment slope (S) and average main river slope (S_{CH}) are also much steeper (see Table 2).

The linear regression plots of the paired Q_{Pxi} and Q_{Di} values applicable to the Central Interior and South Western Coastal regions are shown in Figures 5 and 6 respectively.

At a regional level, the paired Q_{Pxi} and Q_{Di} values showed an acceptable degree of association with r^2 values between 0.4 and 0.7. The r^2 values deviated similarly or less from unity at a catchment level, and such deviations could be ascribed to non-linear changes in the rainfall pattern and catchment conditions (e.g. soil moisture status) between individual flood events in a particular catchment. Consequently, Gericke and Smithers (2015) proposed the use of correction factors to provide individual catchment responses associated with a specific flood event. However, in this study, Equation 15 is used to confirm the validity and representativeness of the sample means, using Equation 14, and thus the correction factors were not applied. The high degree of association (r^2 > 0.99) between Equations 14 and 15 (see Table 4) also confirmed that the extracted flood events in each catchment reflect the actual catchment processes, and, despite the variability of individual catchment responses, does not result in large differences in average catchment values.

Comparison of indirect and direct T_C estimation (channel flow regime)

In Figures 7 and 8 box plots are used to highlight the inherent variability of the T_{Cxi} values estimated directly from the observed streamflow data. In these figures, the whiskers represent the minimum and maximum values, the boxes the 25th and 75th percentile values, and the change in box colour represents the median value. The results of the six equations (Equations 7 to 12) used to estimate T_C, under predominant channel flow conditions, are also super-imposed on Figures 7 and 8, while the goodness-of-fit (GOF) statistics for the test of these equations in the 12 catchments are listed in Tables 5 and 6 respectively.

In practical terms, the high T_{Cxi} variability evident in these figures would not be easily incorporated into design hydrology. Consequently, a reasonable catchment T_{Cx} value for design purposes and for the calibration of empirical equations should be a convergence value based on the similarity of the results obtained when Equations 14 and 15 are used in combination. As mentioned before, the results based on Equations 14 and 15 were compared in each catchment to establish their degree of association, but the results based on Equation 15 were accepted as the most representative catchment T_{Cx} values (shown as red circle markers in Figures 7 and 8). Furthermore, it is clearly evident from Figures 7 and 8 that the high variability in T_{Cxi} estimation is directly related and amplified by the catchment area, with variations up to ± 800% (see Tables 5 and 6, with the bias ranging between –86% and 729%). The Bransby-Williams (Equation 7) and Colorado-Sabol (Equation 12) equations are the only equations which include the catchment area as an independent variable; therefore it is not surprising that it demonstrated poorer results in the larger catchment area ranges (A > 5 000 km^2) of the Central Interior as opposed to the medium catchment area ranges (50 < A ≤ 3 000 km^2) of the South Western Coastal region. It could also be argued that the differences are because the Bransby-Williams equation (Equation 7) was derived from Australian rural catchments, which are decidedly different to South African catchments and with the catchment areas used in the calibration limited to ± 130 km^2. However, the Colorado-Sabol

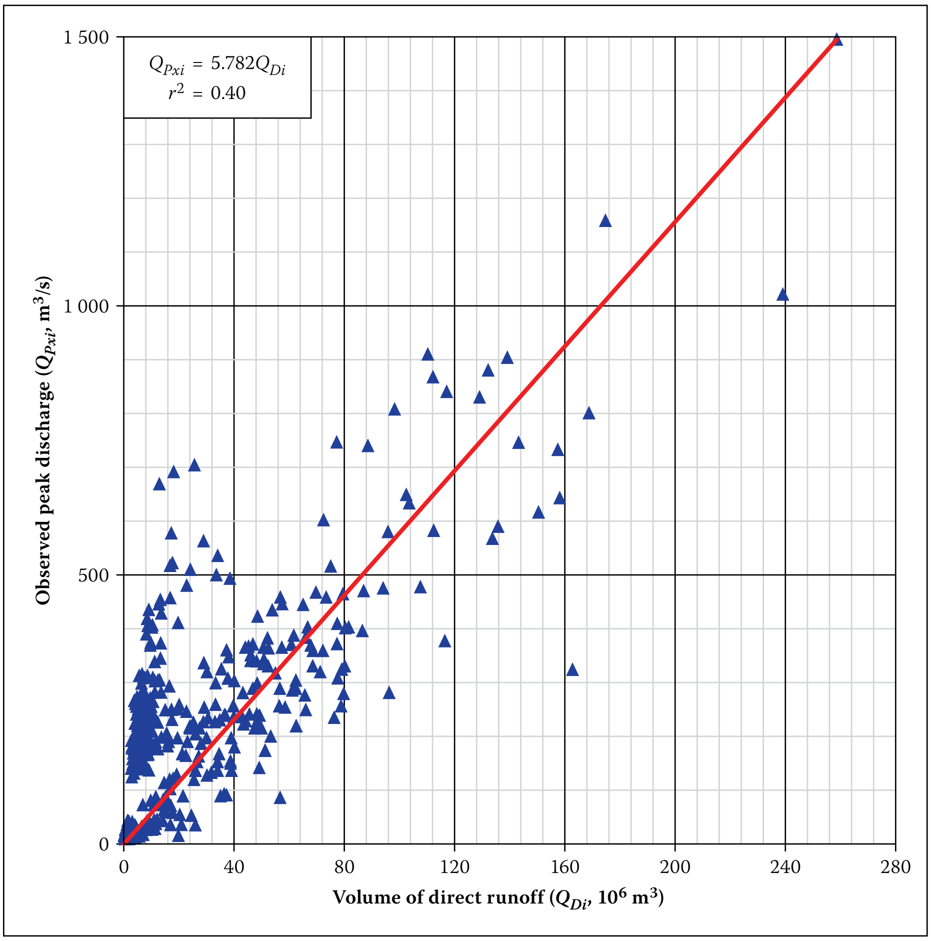

Figure 6 Direct estimation of T_{Cx} (Eq 15) from observed streamflow data (South Western Coastal region)

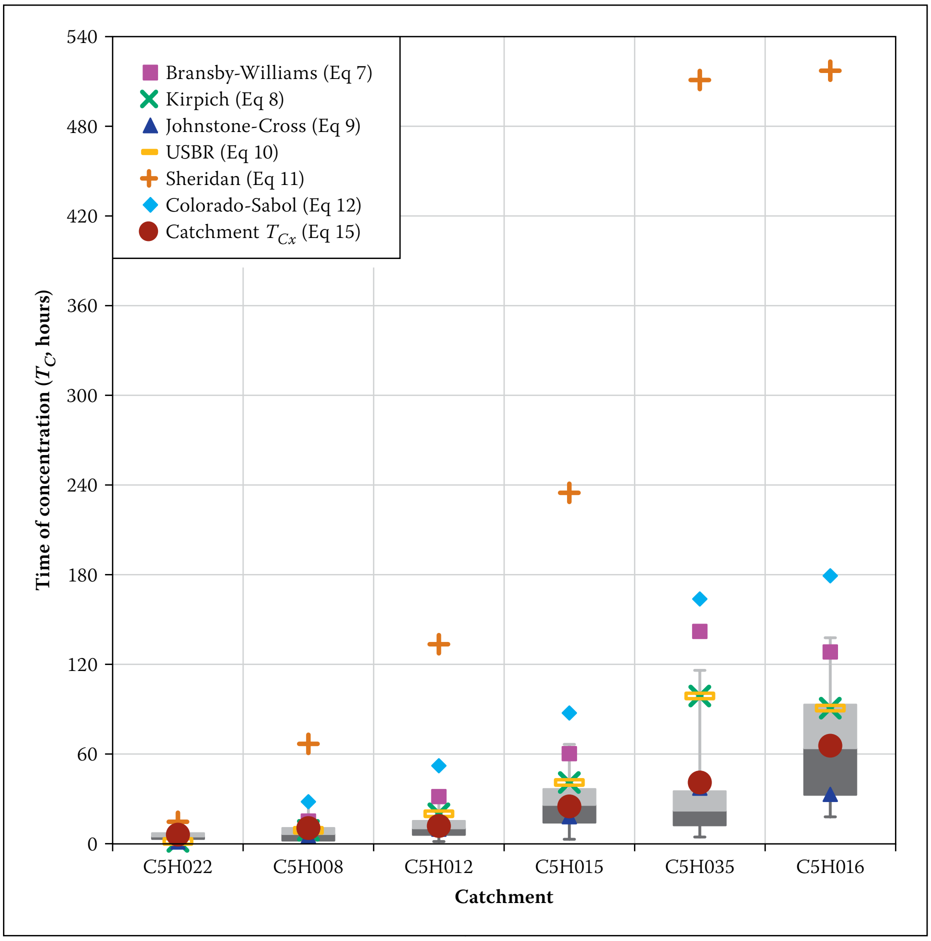

Figure 7 Box plots of T_{Cxi} values (Eq 14) and super-imposed data series values of the catchment T_{Cx} (Eq 15) and empirical T_C estimates for the six catchments of the Central Interior

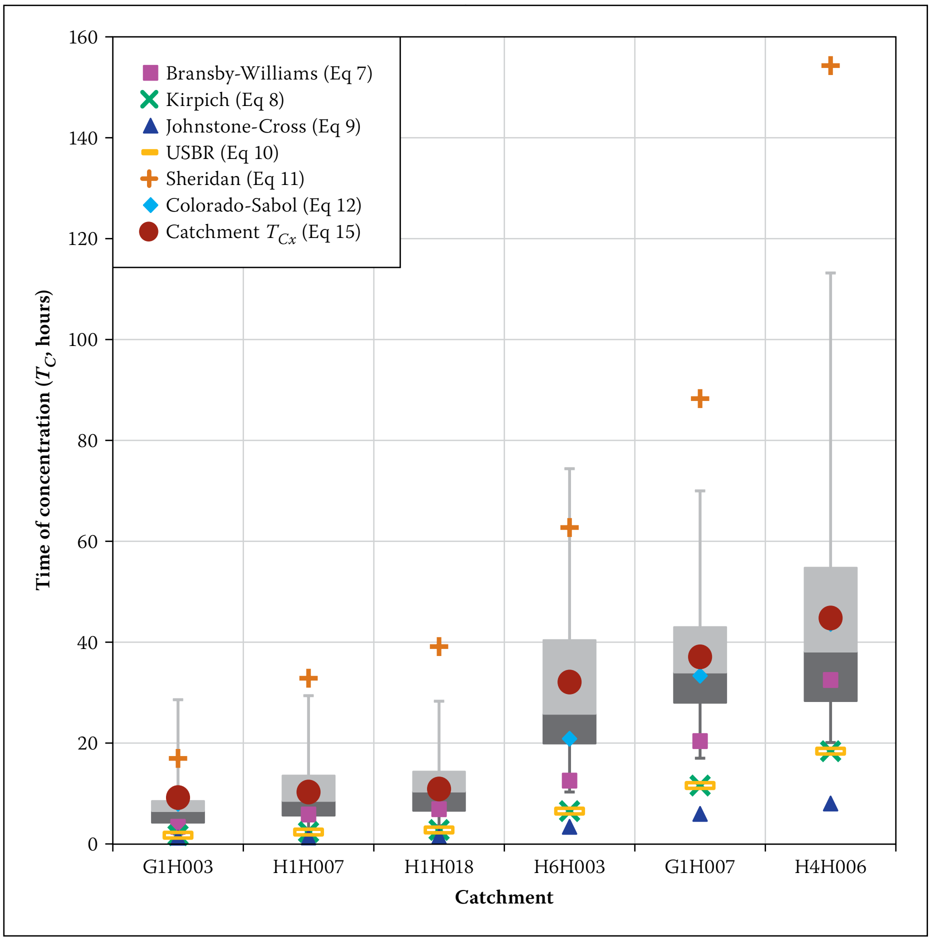

Figure 8 Box plots of T_{Cxi} values (Eq 14) and super-imposed data series values of the catchment T_{Cx} (Eq 15) and empirical T_C estimates for the six catchments of the South Western Coastal region

Table 5 GOF statistics for the testing of channel flow T_C estimation equations compared to the direct estimation of T_{Cx} from observed streamflow data in the Central Interior

Equations	GOF statistics					
	Mean observed T_{Cx} (hrs)	Mean estimated T_C (hrs)	Standard bias statistic (Eq 16) (%)	Mean error (hrs)	Maximum error (hrs)	Standard error (hrs)
Bransby-Williams (Eq 7)	26.7	63.4	107.0	36.7	101.1	10.6
Kirpich (Eq 8)	26.7	43.5	37.1	16.8	57.8	10.3
Johnstone-Cross (Eq 9)	26.7	17.4	–39.7	–9.3	–32.6	11.2
USBR (Eq 10)	26.7	43.5	37.2	16.9	57.9	10.3
Sheridan (Eq 11)	26.7	246.3	728.8	219.6	469.9	8.8
Colorado-Sabol (Eq 12)	26.7	86.2	205.9	59.5	122.7	7.7

Table 6 GOF statistics for the testing of channel flow T_C estimation equations compared to the direct estimation of T_{Cx} from observed streamflow data in the South Western Coastal region

Equations	GOF statistics					
	Mean observed T_{Cx} (hrs)	Mean estimated T_C (hrs)	Standard bias statistic (Eq 16) (%)	Mean error (hrs)	Maximum error (hrs)	Standard error (hrs)
Bransby-Williams (Eq 7)	24.1	13.6	–46.1	–10.5	–19.5	6.2
Kirpich (Eq 8)	24.1	7.2	–73.4	–16.8	–26.4	6.1
Johnstone-Cross (Eq 9)	24.1	3.6	–86.0	–20.5	–36.8	5.0
USBR (Eq 10)	24.1	7.2	–73.4	–16.8	–26.4	6.1
Sheridan (Eq 11)	24.1	65.7	173.4	41.6	109.5	7.0
Colorado-Sabol (Eq 12)	24.1	21.2	–9.4	–2.8	–11.2	4.8

equation (Equation 12), which was derived for catchment areas up to 5 150 km^2, demonstrated slightly poorer results when compared to Equation 7 in the Central Interior with predominantly larger catchments areas. Therefore, the inclusion of the catchment area as an independent variable is not the obvious reason why results are poorer in this case, but it actually confirms that when different empirical equations are applied outside the bounds of their original developmental regions, their calibration exponents are no longer valid. In addition, all the independent variables contained in Equations 7 to 12 are generally regarded as both conceptually and physically acceptable predictors, i.e. the size and shape (A), distance (L_C and L_{CH}) and slope (S_{CH}) predictors would arguably provide a good indication of catchment storage effects (attenuation and travel time). The latter re-emphasises that the poorer results obtained are not due to the use of inappropriate catchment response variables, but could be attributed to the use of empirical equations without local correction factors being applied.

In considering the overall average GOF statistics as listed in Tables 5 and 6, the six empirical equations showed different biases when compared to the 'direct measurement' of T_{Cx}. In the Central Interior (Table 5) only the Johnstone-Cross equation (Equation 9) underestimated the T_{Cx} and it also showed a relatively low bias (–39.7%) and mean error (–9.3 hours). The Kirpich (Equation 8) and USBR (Equation 10) equations, with almost identical results, provided the smallest positive biases (≈ 37.1% each), and associated positive mean errors of ≈ 16.8 hours. The similarity of the latter results could be ascribed to the fact that Equation 10 (USBR, 'recommended' for use in SA) is essentially a modified version of the Kirpich equation (Equation 8). In contradiction to the Central Interior results, as contained in Table 5, the Bransby-Williams (Equation 7) and Colorado-Sabol (Equation 12) equations provide some of the best estimates in the South Western Coastal region (Table 6), with biases of ≤ 46.1% and associated mean errors of ≤ 10.5 hours. However, all the mean error results must be clearly understood in the context of the actual travel time associated with the size of a particular catchment, since in the latter region some of the catchments have average T_{Cx} values < 10 hours.

On average, all the other empirical equations, except the Johnstone-Cross equation (Equation 9), overestimated the T_{Cx} in the Central Interior (Table 5) with maximum absolute errors up to 470 hours, while the opposite is evident from Table 6 (South

Western Coastal region). In the latter region, T_{Cx} was underestimated in all cases, except for Equation 11 (Sheridan). However, the poorest results in both the Central Interior and South Western Coastal regions are also demonstrated by Equation 11, with maximum absolute errors of between 110 hours and 470 hours. Typically, the large errors associated with the Sheridan equation (Equation 11) could be ascribed to the inclusion of only one independent variable (e.g. main watercourse length) to accurately reflect the catchment T_{Cx}.

The conclusions are summarised in the following section.

CONCLUSIONS

This paper demonstrates the estimation of T_C using direct and indirect estimation procedures with observed streamflow data and empirical equations respectively. Empirical equations applicable to the overland flow regime were implemented on a conceptualised urban catchment, while both a direct estimation method and empirical equations applicable to channel flow were implemented on two other case study areas. The results clearly display the wide variability in T_C estimates using different equations. In the estimation of overland flow, the variability and inconsistencies demonstrated are most likely due to the fact that the characteristics of the five different flow retardant categories and associated slope-distance classes considered are decidedly different from those initially used to derive and calibrate the relevant equations. In general, the variability and inconsistencies witnessed in the channel flow regime can be ascribed to the equations being applied outside the bounds of their original developmental regions without the use of local correction factors. However, the fact that either improved or poorer results were obtained with a specific empirical equation in either the Central Interior or South Western Coastal region, also confirms that the results obtained are not due to the use of inappropriate independent variables to estimate the catchment response time. The latter could rather be ascribed to the differences in catchment geomorphology. In addition, it could also be argued that the wide variability and inconsistencies are further exacerbated by the discrepancies in the T_C definitions and estimation procedures found in the literature.

The direct estimation procedure considering both the use of an average catchment T_{Cx} value based on the event means of Equation 14 and a linear catchment response function (Equation 15) proved to be an objective and consistent approach to estimate observed T_{Cx} values by using only streamflow data. In using the latter direct estimation procedure, the validity of the approximation $T_C \approx T_P$ was also confirmed to be sufficiently similar at a medium to large catchment scale. In order to accommodate the high variability and uncertainty involved in the estimation of T_C, we recommend that for design hydrology and for the calibration of empirical equations, T_{Cx} should be estimated using the proposed direct estimation procedure. Ultimately, these observed T_{Cx} values can be used to develop and calibrate new, local empirical equations that meet the requirement of consistency and user-friendliness, i.e. including independent variables (e.g. A, L_C, L_{CH} and S_{CH}) that are easy to determine by different practitioners when required for future applications in ungauged catchments. In order to overcome the limitations of an empirical equation calibrated and verified in a specific region, the proposed methodology should also be expanded to other regions, followed by regionalisation. The regionalisation will not only improve and augment the accuracy of the time parameter estimates, but will also warrant the combination and transfer of information within the identified homogeneous hydrological regions.

In conclusion, the results from this study indicate that estimates of catchment response time are inconsistent and vary widely as applied in modern flood hydrology practice in South Africa. Therefore, if practitioners continue to use these inappropriate time parameter estimation methods, this would limit possible improvements when both event-based design flood estimation methods and advanced stormwater models are used, despite the current availability of other technologically advanced input parameters in these methods/models. In addition, not only will the accuracy of the above methods/models be limited, but it will also have an indirect impact on hydraulic designs, i.e. underestimated T_C values would result in over-designed hydraulic structures and the overestimation of T_C would result in under-designs.

ACKNOWLEDGEMENTS

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

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