Evaluation of critical storm duration rainfall estimates used in flood hydrology in South Africa

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Abstract

Design rainfall comprises of a depth and duration associated with a given probability of exceedance or return period. The purpose of the study was to evaluate and compare the methods used in flood hydrology to estimate depth-duration-frequency (DDF) relationships of design rainfall in South Africa based on the critical storm duration or time of concentration (T_C) of a catchment. The influence of the type of rainfall, areal and temporal distribution of rainfall were also investigated to establish if a relationship exists between the catchment area, T_C and areal reduction factors (ARFs). The DDF relationships based on the least-square regression analyses of Log-Extreme Value Type 1 distributions, the modified Hershfield equation, the regionalised South African Weather Service (SAWS) *n*-day design rainfall data and the Regional Linear Moment Algorithm and Scale Invariance (RLMA&SI) approach were compared in 3 distinctive T_C-ranges. The results showed that the RMLA&SI approach can be considered as the preferred DDF relationship in future design flood estimations. The results also showed that a direct relationship exists between the catchment area and T_C, thus ARFs can be explicitly expressed in terms of only the catchment area.

Keywords: Rainfall, depth-duration-frequency, time of concentration, areal reduction factors, design flood

Introduction

Design rainfall comprises of a depth and duration associated with a given probability of exceedance or return period. Short and long duration design rainfall estimations can either be based on point or regionalised data. Rainfall durations less than 24 h are generally classified as short, while long durations typically range from 1 to 7 days (Smithers and Schulze, 2004).

Several regional and national scale studies in South Africa based on short durations and point data were conducted between 1945 and 2001. The studies focusing on long durations based on daily point rainfall data included studies done by the SAWB (South African Weather Bureau) (1956), Schulze (1980), Adamson (1981), Pegram and Adamson (1988) and Smithers and Schulze (2000b). Smithers and Schulze (2000a; 2000b) also used a regionalised approach in an attempt to increase the reliability of the design values at gauged sites, as well as for the estimation of design values at ungauged sites (Smithers and Schulze, 2003).

Irrespective of whether a single site or regional approach is followed, the design rainfall depth to be used in design flood estimation, especially in the deterministic methods, must be based on the critical storm duration or time of concentration (T_C) of a catchment.

This paper attempts to provide preliminary insight into the applicability of the various methods used in South Africa to estimate design rainfall. The purpose of the study is discussed and explained in the next section, followed by an overview of the study area's spatial distribution and characteristics. Thereafter, the methods used in South Africa to estimate T_C, depth-duration-frequency (DDF) relationships and areal reduction factors (ARFs) are reviewed in detail. The methodologies involved in assessing the paper's purpose and objectives are then expanded on in detail, followed by the results, discussion, conclusions and recommendations.

Purpose of study

The purpose of the study was to evaluate the methods used in flood hydrology to estimate DDF relationships of design rainfall in South Africa, based on the critical storm duration or T_C of a catchment, in 3 distinctive T_C-ranges. The focus was not necessarily to establish the best method; the results from the different methods were compared to highlight any inherent shortcomings present in these methods. In catchments where T_C exceeded 24 h, the different methods were compared to the regionalised South African Weather Service (SAWS) daily design rainfall database (after Smithers and Schulze, 2000b). For T_C less than 24 h, the Regional Linear Moment Algorithm and Scale Invariance (RLMA&SI) approach for estimating design rainfall (after Smithers and Schulze, 2000a) was used as the reference method. These 2 reference methods were used to assess the relative accuracy of all the other available methods. The influences of the type of rainfall and point-to-point differences in the areal and temporal distribution of rainfall were also investigated. This was done to establish whether a relationship exists between the catchment area, T_C and ARFs.

Firstly, it was hypothesised that runoff depends not only on the amount and intensity of rainfall, but is also affected by the duration, size, uniformity, velocity and direction of a storm passing over a catchment. Secondly, it was hypothesised that flood-causing storms have durations just long enough to allow runoff from all parts of the catchment to contribute simultaneously to the flood peak; hence the relationship between the critical duration of a storm and T_C. Thirdly, it was hypothesised that flood-producing storm rainfall is almost never evenly distributed, both in time and space, over an area. Lastly, it was hypothesised that water engineers and other consultants

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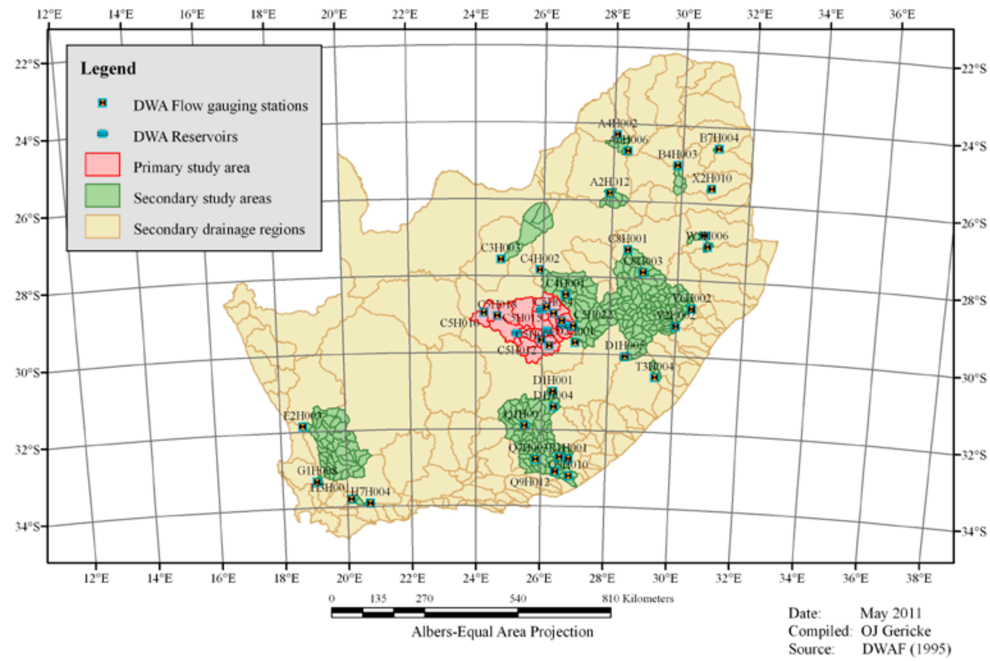

Figure 1
Primary (C5 secondary drainage region) and secondary study areas (South Africa)

(not necessarily hydrologists) tend to use only well-known and simplified DDF relationships to estimate design rainfall depths, irrespective of whether numerical or graphical procedures are used. This is probably due to the direct statistical analysis that needs to be conducted to convert daily observed point rainfall to a design rainfall depth associated with T_C, as well as the uncertainty of the relative applicability thereof and whether the rainfall magnitude-frequency relationships will be satisfactorily accommodated in these alternatives. In addition, Weddepohl (1988), highlighted that the malfunctioning of rainfall gauges, the spatial density and distribution of rainfall gauges, sporadic rainfall events as opposed to the continuous digitised data in use, length of available records and the presence of outliers are all problems inherently contributing to errors in rainfall and subsequently the tendency to use existing DDF relationships to estimate design rainfall in South Africa.

Study areas

The primary study area covers 34 795 km², between 28°25' and 30°17' South and 23°49' and 27°00' East and comprises the C5 secondary drainage region in South Africa. The Riet River and Modder River catchments are the 2 tertiary catchments in the main study area. The area is characterised by the following land uses: 99.1% rural, 0.7% urbanised and 0.2% water bodies (CSIR, 2001). The natural vegetation is dominated by Grassland of the interior plateau, False Karoo and Karoo (light bush). Cultivated land is the largest human-induced vegetation alteration in the rural areas, while residential and suburban areas dominate the urban areas. The topography is gentle (slopes between 2.4% and 5.5%) and water tends to pool easily, thus influencing the attenuation and translation of floods. The mean annual precipitation (MAP) is 424 mm, ranging from 275 mm in the west to 685 mm in the east. It is characterised as highly variable and unpredictable. The rainy season is from early September to mid-April, with a dry winter (Midgley et al., 1994).

To enhance the understanding of the results obtained from this study, as well as to illustrate the relevance thereof in a South African context in different climatic regions, 29 additional catchments, ranging from 28 km² to 29 328 km², were randomly selected in South Africa as secondary study areas. The results (catchment areas and T_C) from previous research conducted by Petras and Du Plessis (1987) and Parak and Pegram (2006) were used as default input parameters to evaluate the current DDF relationships in use.

The location of the primary and secondary study areas is shown in Fig. 1.

Review of Critical Storm Duration Rainfall

The following provides a review of the methods used in South Africa to estimate T_C, DDF relationships and ARFs.

Time of concentration

T_C (Eq. (1)) can be defined as the time required for runoff, as a result of rainfall with a uniform areal and temporal distribution, to contribute to the peak discharge at the catchment outlet. Thus, the time required for a water particle to travel from the catchment boundary along the longest watercourse to the catchment outlet (Rooseboom et al., 1993; SANRAL, 2006). In determining T_C, overland flow and/or flow in defined watercourses and/or artificial/man-made canals (urban areas) can occur.

$$T_C = T_{C1} + T_{C2} + T_{C3} \quad (1)$$

where:

T_C = total time of concentration (h)
T_{C1} = time of concentration for overland flow (h), as shown in Eq. (2)
T_{C2} = time of concentration for flow in defined watercourses (h), as shown in Eq. (3)
T_{C3} = time of concentration for flow in artificial/man-made canals (h), as shown in Eq. (4)

Overland flow occurs in small, relatively flat catchments or in the upper reaches of a catchment, where there is no clearly defined watercourse. Runoff occurs in the form of thin layers of

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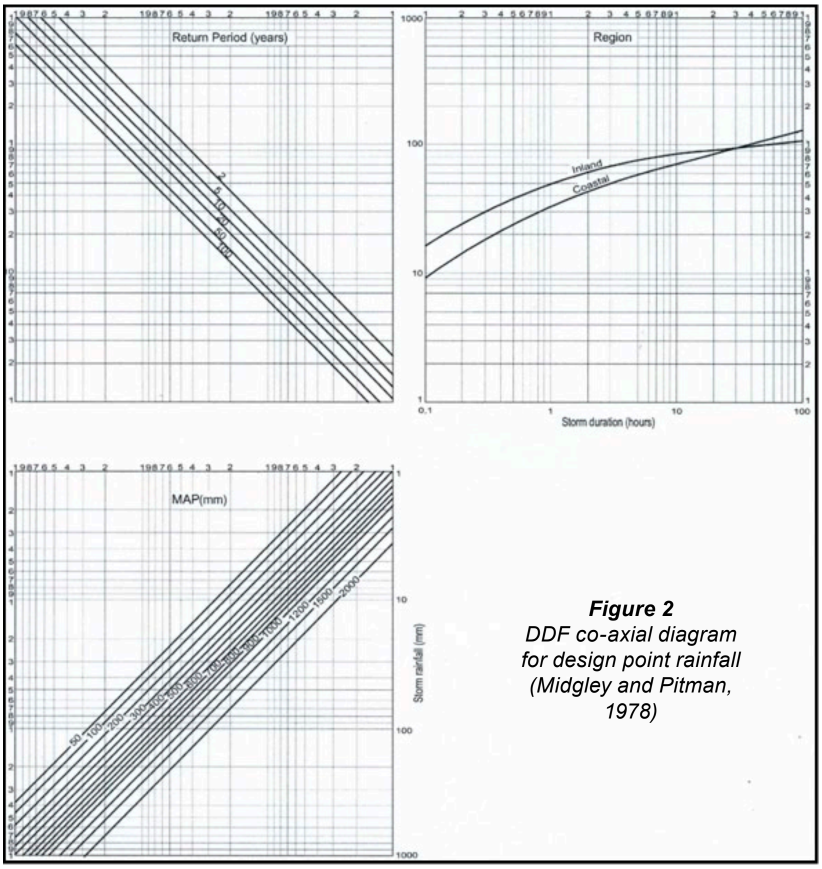

Figure 2
DDF co-axial diagram for design point rainfall (Midgley and Pitman, 1978)

water flowing slowly over the surface. The Kerby equation (Eq. (2)) is applicable to overland flow conditions (Rooseboom et al., 1993; SANRAL, 2006).

$$T_{C1} = 0.604\left(\frac{rL}{\sqrt{\frac{H}{1000L}}}\right)^{0.467} \quad (2)$$

where:

H = height difference along flow path (m)
L = hydraulic length of flow path (km)
r = roughness coefficient.

The roughness coefficient (r) depends on the land use or cover along the flow path, and typically varies between 0.02 (paved areas) to 0.8 (thick grass cover) (SANRAL, 2006). It is similar to Manning's n-value and, according to McCuen (2005), representative roughness coefficient values can be estimated by selecting a basic roughness coefficient value followed by a 5-step correction process, whereby the coefficients are corrected for flow path irregularities and variations, presence of obstructions, vegetation differences and flow path meandering.

Channel flow occurs in a defined watercourse. The United States Department of Agriculture Soil Conservation Service (USDA-SCS) recommends the use of Eq. (3), while Kirpich (1940) recommends the use of Eq. (4) to determine T_C in a natural, defined watercourse.

$$T_{C2} = \left(\frac{0.87L^2}{1000S_{Avg}}\right)^{0.385} \quad (3)$$

$$T_{C2} = 0.0633\left(\frac{L^2}{S_{Avg}}\right)^{0.385} \quad (4)$$

where:

L = length of longest watercourse (km)
S_{Avg} = average main watercourse slope ($m{\cdot}m^{-1}$)

In urban areas or artificial/man-made canals, T_C must be based on the calculated flow velocity estimated using the Chézy or Manning equations. Permissible velocity ranges, based on the material used, must be adhered to (Rooseboom et al., 1993; SANRAL, 2006) and T_C for flow in artificial/man-made canals can be estimated using Eq. (5) (SANRAL, 2006).

$$T_{C3} = \left(\frac{L}{3600\overline{v}}\right) \quad (5)$$

where:

L = length of artificial/man-made canal (m)
$\overline{v}$ = average velocity ($m{\cdot}s^{-1}$)

DDF relationship based on Log-Extreme Value Type 1 (LEV1) distributions

Midgley and Pitman (1978), referred to as M&P in this paper, developed a DDF co-axial diagram (Fig. 2) in which the design point rainfall is a function of the critical storm duration (T_C), regional location (regional factors), probability of exceedance (frequency factors) and MAP.

According to Schulze (1984), there are some anomalies in the database used, since the LEV1 distribution estimated physically impossible rainfall values in some cases. Sinske (1982) emphasised the practical difficulties of using the co-axial diagram and on deciding whether a summer/inland or winter/coastal estimate is applicable to the site of concern. Adamson (1981) indicated that storms shorter than 2 h in duration are likely to be independent of the MAP. Least-square regression analyses were used to derive relationships from the data used by Midgley and Pitman (1978; as cited in Alexander, 2001). These relationships are provided in Eqs. (6) to (9):

$$P = (I_{W,S})\,(T_C)\,(M_F)\,(F) \quad (6)$$

$$I_W = \frac{122.8}{(1+4.779T_C)^{0.7372}} \quad (7)$$

$$I_S = \frac{217.8}{(1+4.164T_C)^{0.8832}} \quad (8)$$

$$M_F = \frac{(18.79+0.17MAP)}{100} \quad (9)$$

where:

F = frequency factor
I_S = rainfall intensity in summer/inland regions ($mm{\cdot}h^{-1}$)
I_W = rainfall intensity in winter/coastal regions ($mm{\cdot}h^{-1}$)
MAP = mean annual precipitation (mm)
M_F = MAP factor
P = rainfall depth (mm)
T_C = time of concentration (h)

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The frequency factors (F), based on the relationship between the design rainfall depths and various return periods, are listed in Table 1.

Table 1
Frequency factors (Midgley and Pitman, 1978; Alexander, 2001)

Return period (T, years)	Frequency factors (F)
2	0.47
5	0.64
10	0.81
20	1.00
50	1.30
100	1.60
200	1.80

DDF relationship based on the Technical Report 102 (TR102) daily rainfall data

The 1, 2, 3 and 7-day extreme design rainfall depths for return periods of 2, 5, 10, 20, 50, 100 and 200 years were estimated by Adamson (1981) using approximately 2 400 rainfall stations. A censored Log-Normal (LN) distribution based on the Partial Duration Series (PDS) was used in this study to estimate the design rainfall depths at a single site. According to Adamson (1981), the daily rainfall depth recorded at fixed 24-h intervals can be converted to a continuous 24-h rainfall depth by making use of the relationship provided in Eq. (10). However, this approach is outdated and Smithers and Schulze (2000a) developed regionalised relationships for 15 relatively homogeneous rainfall regions in South Africa, with a national average of 1.21.

$$P_{24h} = 1.11 P_{1\ day} \tag{10}$$

where:

P_{24h} = 24-h rainfall depth (mm)
$P_{1\text{-}day}$ = 1-day rainfall depth (mm)

The computed ratios for the T_C (hour) duration storm depth to that for 24 h, for the summer/inland and winter/coastal rainfall regions, are listed in Table 2.

Table 2
Ratio of T_C (hours) storm depth to 24 hour storm depth (Adamson, 1981)

T_C (hours)	Summer/inland region	Winter/coastal region
0.10	0.17	0.14
0.25	0.32	0.23
0.50	0.46	0.32
1	0.60	0.41
2	0.72	0.53
3	0.78	0.60
4	0.82	0.67
5	0.84	0.71
6	0.87	0.75
8	0.90	0.81
10	0.92	0.85
12	0.94	0.89
18	0.98	0.96
24	1.00	1.00

Converting daily design rainfall depths to durations longer than 1 day simply entails the conversion of fixed interval to continuous measurement (e.g.1 day to 24 h, 2 days to 48 h), and interpolating between the different duration (h) rainfall depths as given in Table 3. However, this simple approach is outdated and no literature is available as to how these ratios were derived. In the next section, the regional approach proposed by Smithers and Schulze (2000b) is discussed as the preferred design rainfall database to TR102.

Table 3
Conversion of daily to hourly rainfall (Van der Spuy and Rademeyer, 2008)

Duration		Conversion factor
From (days)	To (hours)	
1	24	1.11
2	48	1.07
3	72	1.05
4	96	1.04
5	120	1.03
7	168	1.02
> 7	> 168	1

DDF relationship based on the regionalised SAWS daily rainfall data

Smithers and Schulze (2000b) conducted direct statistical analyses based on the General Extreme Value (GEV) probability distribution, at 1 789 rainfall stations with at least 40 years of record, to estimate the 1-day design rainfall values in South Africa. This was followed by a regionalisation process (based on Linear-Moments) and establishment of 78 relatively homogeneous rainfall regions and associated index values derived from at-site data.

Quantile growth curves, representative of the ratio between design rainfall depth and an index storm to return period, were developed for each of the homogeneous rainfall regions and storm durations of 1 to 7 days. These regionalised growth curves and the at-site index values were then used to estimate design rainfall depths at 3 946 rainfall stations in South Africa (Smithers and Schulze, 2000b).

In this paper, the 3 946 rainfall stations are collectively referred to as the Regional L-Moment Algorithm SAWS n-day design point rainfall database (RLMA-SAWS), since the majority (82.2%) of the daily rainfall stations used, were contributed by the SAWS. The remaining daily rainfall data were provided by the Institute for Soil, Climate and Water (ISCW), the South African Sugar Association Experiment Station (SASEX) and private individuals (Smithers and Schulze, 2000b).

DDF relationship based on the modified Hershfield equation

Alexander (2001) proposed that the modified Hershfield equation (Eq. (11)) must be used to calculate the DDF relationships for durations less than 6 h. For rainfall durations longer than 6 h and less than 24 h, Alexander (2001) recommends linear interpolation between Eq. (11) and the 1-day design point rainfall depth from TR102 (Adamson, 1981). If T_C exceeds 24 h, then linear interpolation between the n-day design point rainfall depth values must be used. In this paper, the RLMA-SAWS database (after Smithers and Schulze, 2000b) was used

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instead of TR102, since this database has ± 20 years more data at 3 946 rainfall stations.

$$P = 1.13(0.41 + 0.64 \ln T)(-0.11 + 0.27 \ln(60T_C))(0.79 M^{0.69} R^{0.20}) \quad (11)$$

where:

- M = 2-year mean of the annual daily maxima rainfall (mm)
- P = rainfall depth (mm)
- R = average number of days per year on which thunder was heard
- T = return period (years)
- T_C = time of concentration (h)

DDF relationship based on a regional scale invariant approach

Regional approaches are well established in frequency analysis and various different techniques are available. The use of the RLMA approach by Smithers and Schulze (2000b), to estimate long duration design rainfall, was highlighted in a previous section. The same approach was followed to estimate short duration (< 24 h) design rainfall in South Africa, but it was based on digitised rainfall data from 172 stations which had at least 10 years of data (Smithers and S chulze, 2003; 2004). A scale invariance approach, where the mean Annual Maximum Series (AMS) for any duration can be estimated by firstly estimating the mean 1-day AMS at a single site by regional regression, followed by scaling either the mean AMS for durations shorter or longer than 1 day, respectively, from the 24 h and 1 day values, were used in conjunction with RLMA. This application is referred to as the Regional Linear Moment Algorithm and Scale Invariance (RLMA&SI) approach. A software program, 'Design Rainfall Estimation in South Africa' was developed in 2003 to facilitate the estimation of design rainfall depths at a spatial resolution of 1-arc minute, for any location in South Africa, based on the RLMA&SI approach, for durations ranging from 5 min to 7 days and for return periods of 2 to 200 years (Smithers and Schulze, 2003; 2004).

Areal reduction factor

Design point rainfall estimates are only representative for a limited area, and for larger areas the areal average design rainfall depths or intensities are likely to be less than the maximum observed point rainfall depths or intensities. The estimation of ARFs is concerned with the relationship between the design point and areal rainfall; in other words, ARFs are used to convert design point rainfall depth/intensity to average areal design rainfall depth/intensity for a given duration and catchment area (Alexander, 2001).

In small catchment areas, of less than 800 km², the ARF is mainly a function of the area and design point rainfall intensity, since the relationship between rainfall intensity and the infiltration rate of the soil is predominant. In medium to large catchment areas, up to 30 000 km², the ARF is mainly a function of the area and storm duration, since the quantity of rainfall relative to the number of storage areas is of great importance. In both cases, the ARF decreases in value with an increase in area and is independent of the return period and geographical location. These relationships are clearly evident from the ARF graphs included in the Drainage Manual (SANRAL, 2006). These graphs are based on a variable location, storm-centred analysis, as conducted by the HRU (1972). However, this approach posed conceptual problems when applied to a geographically-fixed catchment and the use of a correction factor was suggested (Alexander, 2001). In response, Alexander (1980) developed a geographically-centred ARF relationship based on the ARFs contained in the United Kingdom Flood Studies Report (UK FSR) (NERC, 1975).

This developed ARF relationship (Eq. (12)), as a function of the catchment area and response time in terms of T_C, resulted in slightly more conservative results when compared to the UK FSR and United States Weather Bureau (USWB) values (Alexander, 2001).

$$ARF = (90\,000 - 12\,800 \ln A + 9\,830 \ln(60T_C))^{0.4} \quad (12)$$

where:

- A = catchment area (km²)
- ARF = areal reduction factor (%)
- T_C = time of concentration (h)

In Eq. (12) the ARF relationship accommodates severe storm mechanisms producing very high intensity rainfall with cell core areas exceeding 10 km^2 and durations exceeding 10 min. Estimates of shorter duration rainfall based on extrapolation from longer durations are unreliable when viewed in the light of the storm mechanisms which produce high-intensity rainfall for durations less than 10 min (Alexander, 2001).

Methodology

This section provides the detailed methodology followed during this study and is based on the theoretical methods reviewed in the previous section.

Averaging of rainfall depth

The arithmetic mean, Thiessen polygon and isohyetal methods were used to convert the point design rainfall depths at 185 rainfall stations (from RLMA-SAWS database) to an average design rainfall depth over the main study area (C5 secondary drainage region). The details (station number, record length, MAP and Thiessen polygon area) of the above-mentioned 185 rainfall stations are listed in Table 4. The same procedure was also followed in 12 quaternary catchments within the main study area. The 29 secondary study areas were analysed similarly, but without using the isohyetal method. A flow gauging station from the Department of Water Affairs (DWA) is situated at the outlet of all the catchments used in the study. The flow gauging station numbers were therefore used as the catchment identifier or descriptor for easy reference.

The Areal Rain extension in ArcView 3.2a was used to generate Thiessen polygons representative of the averaged design rainfall depths for a particular area (catchment) from design point rainfall measurements. The boundary of the resultant Thiessen polygons was selected in each case either by the applicable quaternary catchments (polygon feature classes) or by a buffered group of rainfall stations (point feature classes). The latter option provides an alternative that allows the user to include rainfall stations located outside the catchment boundary. The rainfall station number field in the attribute table of the point feature class (rainfall stations) was used to identify points and rainfall. The attribute table was then automatically updated; fields (Thiessen area, total area, weighted area, Thiessen and areal rainfall) were added with the geometry (area) being calculated. These attribute tables were

Table 4
185 RLMA-SAWS rainfall stations used in the primary study area (C5)

Number	Rainfall station	Record length (years)	MAP (mm)	Thiessen polygon area (km²)
1	0201361W	86	414	140.7
2	0201370W	42	435	227.9
3	0201373W	53	453	143.4
4	0201482W	86	414	108.8
5	0201492W	43	453	129.0
6	0201637W	37	340	123.9
7	0201756W	28	361	81.7
8	0201843W	29	382	147.6
9	0228571W	68	332	171.5
10	0228725W	52	314	223.6
11	0228783W	56	334	133.9
12	0229124W	59	370	178.2
13	0229215W	43	366	176.6
14	0229344W	52	401	190.8
15	0229555W	51	420	75.8
16	0229556W	33	422	109.7
17	0229571W	50	368	172.7
18	0229579W	40	398	210.1
19	0229629W	47	405	209.0
20	0229654W	36	374	178.6
21	0229723W	47	368	158.5
22	0229737W	99	414	138.4
23	0229862W	37	384	115.3
24	0230011W	54	426	194.9
25	0230027W	81	466	220.9
26	0230048W	42	376	124.1
27	0230073W	76	419	48.2
28	0230074W	24	395	52.7
29	0230210W	34	395	286.1
30	0230254W	39	359	178.2
31	0230349W	27	409	194.9
32	0230363W	41	275	342.9
33	0230466W	31	389	233.2
34	0230542W	44	384	181.0
35	0230566W	39	368	147.0
36	0230598W	30	410	79.1
37	0230764W	91	427	244.4
38	0230774W	62	431	186.8
39	0230810W	93	408	118.8
40	0230816W	75	489	265.2
41	0231076W	44	386	180.0
42	0231114W	35	431	422.3
43	0231161W	49	406	128.2
44	0231247W	35	463	120.9
45	0231279W	93	479	80.2
46	0231361W	64	459	139.4
47	0231375W	47	403	241.1
48	0231395W	71	454	146.2
49	0231588W	37	443	237.7
50	0231663W	26	496	112.4
51	0231713W	56	479	362.4
52	0231754W	55	516	111.8
53	0231761W	31	564	191.0
54	0232011W	41	530	129.1
55	0232018W	86	420	97.7
56	0232123W	88	555	127.0
57	0232181W	58	555	96.2
58	0232211W	88	555	40.1
59	0232275W	94	585	102.4
60	0232301W	38	488	74.0
61	0232512W	35	599	98.5
62	0256638W	78	293	389.5
63	0257391W	66	332	1 583.0
64	0257845W	85	364	381.8
65	0257878W	36	358	332.9
66	0258079W	38	305	483.8
67	0258157W	32	385	67.9
68	0258164W	70	322	161.6
69	0258182W	85	359	858.9
70	0258213W	41	404	57.7
71	0258218W	50	359	49.1
72	0258306W	68	348	27.5
73	0258335W	50	375	156.6
74	0258339W	51	374	49.2
75	0258380W	63	275	147.3

Table 4 (continued)

Number	Rainfall station	Record length (years)	MAP (mm)	Thiessen polygon area (km²)
76	0258399W	51	325	33.2
77	0258434W	51	363	90.0
78	0258458W	98	376	115.6
79	0258467W	51	349	101.8
80	0258474W	34	313	128.2
81	0258581W	56	342	197.7
82	0258624W	63	338	129.9
83	0258740W	51	350	115.4
84	0258812W	70	349	129.6
85	0258827W	44	360	179.4
86	0258894W	99	450	145.0
87	0259002W	45	363	127.3
88	0259086W	25	359	189.3
89	0259102W	31	371	155.2
90	0259131W	30	392	109.1
91	0259278W	67	414	211.3
92	0259348W	71	369	378.2
93	0259390W	29	408	239.6
94	0259578W	57	426	154.3
95	0259609W	49	399	141.3
96	0259727W	94	411	144.6
97	0259743W	64	309	272.9
98	0259855W	43	463	118.7
99	0259881W	54	433	105.5
100	0259887W	49	457	98.5
101	0260004W	89	449	98.4
102	0260030W	80	374	238.3
103	0260082W	33	448	126.3
104	0260083W	33	424	172.5
105	0260126W	32	454	199.8
106	0260163W	74	461	127.8
107	0260314W	39	440	218.4
108	0260519W	66	471	367.2
109	0260555W	50	516	181.2
110	0260660W	47	459	140.8
111	0260678W	88	478	213.1
112	0260715W	36	373	253.3
113	0260882W	56	495	336.0
114	0261146A	86	479	250.9
115	0261183W	95	484	276.0
116	0261256W	36	325	248.0
117	0261266W	36	519	176.9
118	0261275W	60	570	50.0
119	0261307W	25	537	51.4
120	0261312W	63	538	103.5
121	0261365W	73	558	43.7
122	0261366W	39	563	7.0
123	0261367W	46	552	7.0
124	0261368W	88	545	10.9
125	0261369W	47	613	39.7
126	0261425W	46	553	45.5
127	0261426W	30	553	15.0
128	0261516W	42	537	56.0
129	0261517W	37	514	16.2
130	0261523W	94	518	191.9
131	0261548W	26	518	73.0
132	0261597W	53	426	256.7
133	0261722W	94	534	221.9
134	0261733W	70	486	171.5
135	0261750W	55	497	149.3
136	0261789W	27	551	142.8
137	0261890W	36	523	342.6
138	0262129W	70	516	143.5
139	0262155W	32	473	132.7
140	0262247W	24	566	113.6
141	0262271W	28	435	140.5
142	0262314W	54	526	250.4
143	0262353W	52	530	296.5
144	0262453W	24	548	183.9
145	0262479W	94	554	125.6
146	0262613W	76	590	242.2
147	0262690W	47	548	115.3
148	0262734W	43	649	70.4
149	0262828W	30	686	147.2
150	0290810W	64	380	357.5
151	0290887W	45	392	487.5
152	0291075W	32	441	146.0
153	0291148W	90	397	70.0

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Table 4 (continued)				
Number	Rainfall station	Record length (years)	MAP (mm)	Thiessen polygon area (km²)
154	0291174W	34	375	109.5
155	0291178W	59	396	66.1
156	0291231W	42	333	107.9
157	0291313W	44	431	242.4
158	0291323W	29	404	100.3
159	0291360W	44	403	196.8
160	0291415W	46	394	209.2
161	0291582W	39	449	225.2
162	0291708W	47	390	292.1
163	0291758W	33	418	337.4
164	0291899W	85	433	201.7
165	0292051W	41	398	379.6
166	0292089W	36	430	162.8
167	0292446W	35	438	509.0
168	0292461W	90	432	576.3
169	0292606W	40	455	155.5
170	0292833W	47	453	435.5
171	0293007W	66	453	446.7
172	0293106W	71	471	301.5
173	0293204W	61	478	293.7
174	0293339W	35	406	224.3
175	0293403W	24	463	240.2
176	0293514W	73	486	300.9
177	0293568W	38	464	140.6
178	0293597W	40	529	90.1
179	0293622W	70	500	153.7
180	0293652W	75	500	141.7
181	0293700W	66	476	189.6
182	0293792W	90	536	228.1
183	0294052W	53	428	284.5
184	0294233W	85	471	213.6
185	0294417W	67	506	153.9

then exported as a database file (dbf) to use Microsoft Excel for further computations.

In the case of the isohyetal method, the Spatial Analyst Tools (Interpolation and Reclass) extension in ArcGIS™ 9.3 was used to generate and reclassify a MAP Raster (based on the design point rainfall depths at 3 946 rainfall stations contained in RLMA-SAWS database) at a defined isohyetal interval of 25 mm. The raster was based on a cell matrix approach, which represents the maximum change in design rainfall over the distance between the cell and its 8 neighbouring cells, thus representative of the maximum average design rainfall for each cell. The Conversion Tools extension was then used to convert the raster to a polygon feature class to enable the determination of the areas associated with each isohyetal interval or MAP range.

The RLMA&SI gridded design point rainfall values were converted into an average catchment value by making use of the following steps:

- **Step 1** – The averaged design rainfall representative of the average meteorological conditions in each catchment was estimated by using the Thiessen polygon method applied to all of the daily design rainfall stations (from the RLMA-SAWS database) within the catchment boundary. Both the MAP and average design rainfall depths (for storm durations of 1 to 7 days) were estimated.
- **Step 2** – A single rainfall station, with a sufficiently long record length and which is representative of the average meteorological conditions as estimated in Step 1, was then selected from those stations used in Step 1 as the base station to estimate the RLMA&SI gridded design point rainfall values.
- **Step 3** – With the single rainfall station as selected in Step 2, the appropriate storm durations (5 min to 7 days), return periods (2 to 200 years) and block size (spatial resolution of 1′x1′ grid points) were selected. The block size was specified in such a way that the whole extent of each catchment under consideration was covered with grid points.
- **Step 4** – Lastly, the gridded point values for each storm duration and return period under consideration were converted to an averaged catchment value by making use of the arithmetic mean.

Critical storm duration rainfall

The design rainfall depths for critical storm durations were estimated based on the following approaches:

- DDF relationship based on LEV1 distributions developed by M&P
- DDF relationship based on the modified Hershfield equation and/or RLMA-SAWS daily design rainfall database as statistically analysed and regionalised by Smithers and Schulze (2000b)
- DDF relationship based on the RLMA&SI approach

The critical storm duration in each case was determined by using Eq. (3), which represents T_C in a natural, defined watercourse. All of the catchments evaluated can be classified as medium to large (only 5% of the catchments have areas < 100 km²) and therefore all overland flow (Eq. (2)) was regarded as main watercourse flow and included as part of the main watercourse flow path length. Eq. (3) was preferred to Eq. (4), since it is generally used and accepted in South Africa, while SANRAL (2006) also recommends the use thereof. The degree of association between these 2 equations is high, but Eq. (4) tends to underestimate the T_C-values compared to Eq. (3). Consequently, this will result in higher peak discharge estimations.

The use of Eq. (5) was discarded, since all of the catchments are rural, with no or a few artificial/man-made canals. In addition, the use of Eq. (5) is very sensitive to selecting the appropriate surface roughness parameter in terms of the Manning's (n) and/or Chézy's (k_s) coefficients. In the case of overland flow, an increase in surface roughness will result in flow retention and subsequently higher potential infiltration rates. An increased roughness in channels will result in lower velocities, deeper flow depths and higher associated flood levels, and a possible reduction in erosion or sediment transport (McCuen, 2005).

Thus, the DDF relationships were then categorised according to 3 T_C-ranges; $T_C \leq 6$ h, $6 < T_C \leq 24$ h and $24 < T_C \leq 168$ h.

Areal reduction factors

The ARF in each catchment under consideration, in other words the conversion of design point rainfall depths or intensities to average areal design rainfall depths or intensities, was established by using Eq. (12). The validity of this equation was assessed by plotting T_C within each catchment under consideration against the catchment area, after which it was superimposed on both an ARF curve based on Eq. (12) and the ARF diagram as published in the UK FSR (NERC, 1975).

Days of thunder per year

The average number of days per year on which thunder was heard (R) is an input parameter required by the modified Hershfield equation (Eq. 11). This parameter is associated with the type of rainfall, e.g. convective rainfall is normally

Table 5
Averaged RLMA-SAWS design rainfall depths of the primary study area (C5)

Duration (days)	Return period (years) / Design rainfall depths (mm)						
	2	5	10	20	50	100	200
Arithmetic mean method							
MAP (mm)					439.0		
2-year mean of annual daily maxima rainfall (*M*)					45.0		
Days of thunder per year (*R*)					57.1		
1	45.0	61.4	72.9	84.4	99.8	111.9	124.5
2	55.6	76.3	90.8	105.4	125.2	140.8	157.1
3	61.5	84.7	101.1	117.7	140.5	158.7	177.8
7	75.8	105.7	127.5	150.0	181.9	208.0	236.1
Thiessen polygon method							
MAP (mm)					424.0		
2-year Mean of annual daily maxima rainfall (*M*)					44.7		
Days of thunder per year (*R*)					56.7		
1	44.7	61.2	72.6	84.1	99.6	111.7	124.2
2	55.1	75.7	90.1	104.7	124.6	140.2	156.5
3	60.7	83.8	100.2	116.8	139.7	158.0	177.2
7	74.6	104.5	126.3	148.9	181.0	207.3	235.8
Isohyetal method							
MAP (mm)					413.0		
2-year mean of annual daily maxima rainfall (*M*)					45.0		
Days of thunder per year (*R*)					56.4		
1	45.0	61.5	73.0	84.4	99.8	111.8	124.1
2	55.9	76.9	91.5	106.2	126.3	142.1	158.5
3	61.4	84.9	101.5	118.4	141.8	160.4	180.1
7	74.5	104.6	126.7	149.7	182.5	209.5	238.8

Table 6
MAP of the 12 catchments within the primary study area (C5)

Catchment description	MAP (mm)			Number of rainfall stations (N_i)
	Arithmetic mean	Thiessen polygon	Isohyetal method	
Study area	439	424	413	185
C5H003	553	549	543	8
C5H012	448	444	434	11
C5H015	530	518	505	47
C5H016	440	429	417	183
C5H018	479	461	448	93
C5H022	686	660	563	3
C5H054	542	523	502	13
C5R001	492	488	473	7
C5R002	421	420	406	61
C5R003	553	549	521	8
C5R004	530	518	505	47
C5R005	642	660	563	3

associated with a higher degree of thunder activities than, for instance, frontal rain. The *R*-values used in this study were based on the climate data as published in the SAWB publication WB 42 (SAWB, 1992) and the generalised isohyetal map contained in Alexander (2001). There are 280 rainfall stations with associated *R*-values in WB 42, thus representing only ± 7% of the total number of rainfall stations available in the RLMA-SAWS database as developed by Smithers and Schulze (2000b).

The above-mentioned isohyetal map and data contained in WB 42 were used to establish *R*-values for the remaining 3 666 rainfall stations by means of linear interpolation. The 280 stations used were also allocated to the 4 synthetic 24-h distribution regions of design rainfall intensity as occurring in southern Africa and commonly used in the Soil Conservation Services (SCS) method (Schulze et al., 1992). Typically, the Type 1 and 2 storm distributions apply to coastal areas with winter rainfall or rainfall throughout the year (frontal), while the Type 3 and 4 storm distributions apply to inland areas characterised by high design rainfall intensities and convection activity. This was done by superimposing the 'Area distribution of storm types in South Africa' map over the 'SAWS rainfall station reference grid' map (SANRAL, 2006).

The *R* and the 2-year mean of the annual daily maxima rainfall (*M*) values were then plotted against one another to establish whether any direct relationship exists which can be

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used to express the *R*-values in terms of the *M*-values. The anticipated results will thus exclude the degree of uncertainty associated with the selection of default *R*-values based on location only.

Table 7
MAP of the 29 secondary study areas (RSA)

Catchment description	MAP (mm)		Number of rainfall stations (N_i)
	Arithmetic mean	Thiessen polygon	
A2H012	726	692	40
A4H002	629	637	7
A6H006	634	630	3
B4H003	709	702	10
B7H004	957	1 086	2
C3H003	527	525	39
C4H001	572	568	31
C4H002	547	541	61
C8H001	687	680	65
C8H003	647	647	1
D1H001	452	460	27
D1H005	703	656	8
D2H001	698	742	65
E2H003	292	234	25
G1H008	712	554	2
H7H004	333	333	1
Q1H001	349	343	35
Q7H003	369	359	78
Q9H004	732	631	4
Q9H008	713	679	10
Q9H010	418	398	111
Q9H012	374	366	89
R1H001	926	791	2
T3H004	779	766	6
V2H002	1 065	1 012	4
V6H002	912	856	29
W5H005	839	832	3
W5H006	887	887	1
X2H010	1 305	1 305	1

Results and discussion

Averaging of rainfall depth

The results of the averaged design rainfall depth calculations applicable to the primary and secondary study areas are listed in Tables 5, 6 and 7 respectively. Figures 3 and 4 are illustrative of the Thiessen polygon and isohyetal weighted areas and location of the daily design rainfall stations within the primary study area, while Fig. 5 serves as a visual comparison between the arithmetic mean, Thiessen polygon and isohyetal methods.

The number of rainfall stations used for averaging the rainfall varied from catchment to catchment with an overall average of 1 station per 100 km². The arithmetic mean values exceeded both the Thiessen polygon and isohyetal values in all of the catchments, with the exception of C5R005. However, this was also the only catchment where the polygons and isohyets were based on rainfall stations within and outside the catchment boundary. The percentage differences between the arithmetic mean and Thiessen polygon methods varied between -3% and 4%, while the arithmetic mean and isohyetal method differed with between 2% and 22%. Similar trends were evident between the Thiessen polygon and isohyetal methods, with differences between 1% and 17%. Despite these percentage differences, the coefficient of determination (r^2) varied between 0.90 and 0.98, which is indicative of an overall high degree of association between these methods. This also confirmed the even areal distribution of the rainfall stations and the relatively flat topography of the C5 secondary drainage region (main study area). Similar results were evident in the secondary study areas.

Critical storm duration rainfall

The design rainfall depths for critical catchment storm durations, estimated using the various DDF relationships for the specific catchments evaluated in the primary and secondary study areas, are listed in Tables 8 to 10.

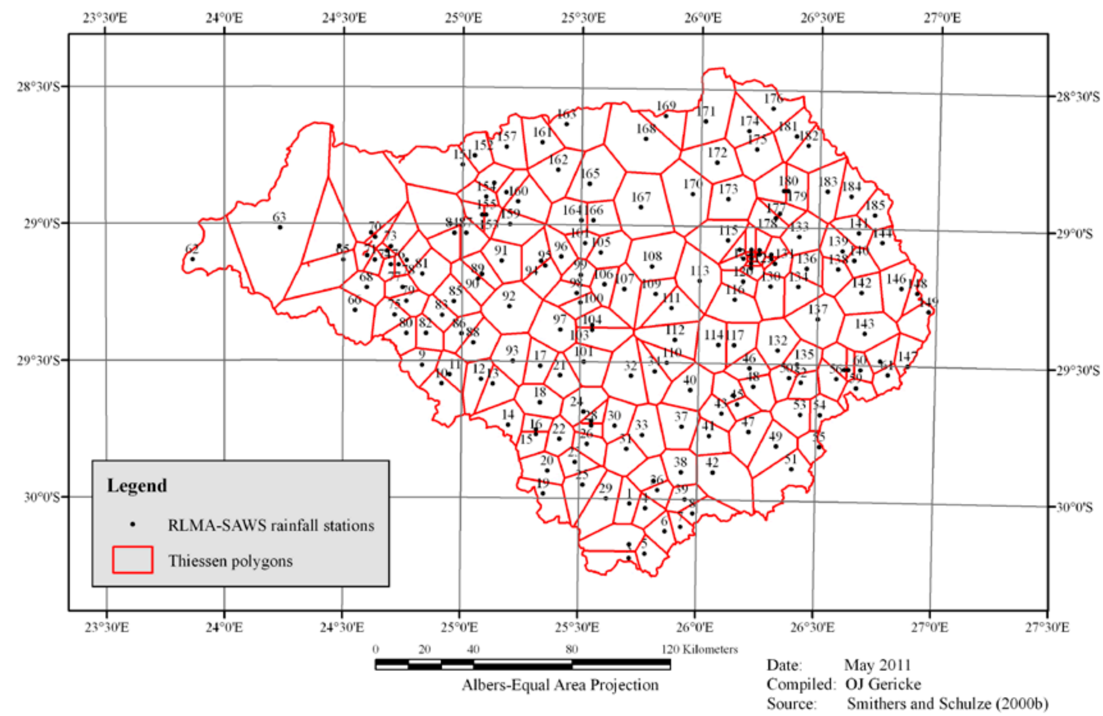

Figure 3 *Thiessen polygons in the primary study area (C5)*

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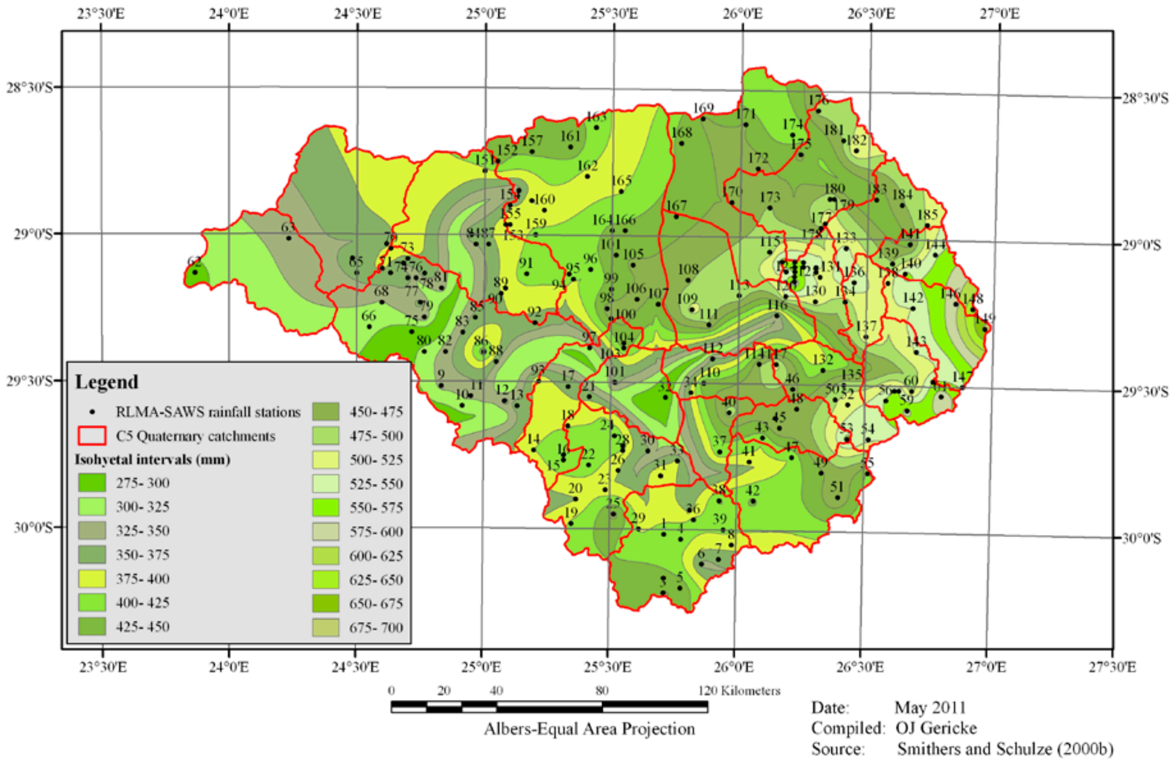

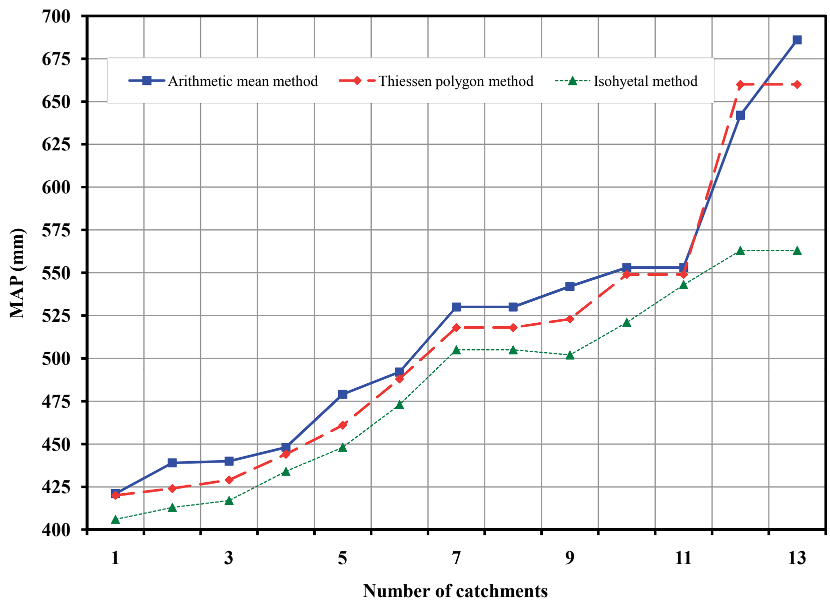

Figure 4 (above)
Map isohyets in the primary study area (C5)

Figure 5 (left)
Comparison between the arithmetic mean, Thiessen polygon and isohyetal methods

The results in Table 8 ($T_C \leq 6$ h) indicated that the design rainfall estimated according to the M&P/LEV1 relationship overestimated the design rainfall depths for all the return periods, when compared to the estimates using the modified Hershfield equation and the RMLA&SI approach, except at the 10- to 50-year return periods in Catchments A6H006 and C5H022. In Catchment H7H004, M&P/LEV1 underestimated all of the design rainfall depths when compared to the 2 other approaches. The coefficient of determination (r^2) was a constant value of 0.76 for each return period when the M&P/LEV1 and Hershfield methodologies within the critical storm duration range under consideration were compared. The degree of association between the M&P/LEV1 and RMLA&SI relationships decreased from 0.77 (10-year) to 0.71 (200-year). Compared to the RLMA&SI approach, the modified Hershfield equation generally slightly underestimated the design rainfall depths for the 10- and 20-year return periods in catchment G1H008, while all of the return periods in Catchment H7H004 were underestimated. The rainfall depths were slightly overestimated in the remaining catchments. The degree of association between these 2 methods was high, since the coefficient of determination varied between 0.93 at the 10-year return period and decreased to 0.87 at the 200-year return period. Figure 6 is illustrative of the average design rainfall depths based on the 3 DDF relationships within the critical storm duration range; $T_C \leq 6$ h for all of the catchments listed in Table 8.

The results in Table 9 ($6 < T_C \leq 24$ h) showed that all the DDF relationships under consideration demonstrated, on average, similar trends, as in the case of the critical storm duration range, $T_C \leq 6$ h, but the overall degree of

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Table 8
Design rainfall depths for $T_c \leq 6$ hours

Catchment description	T_c (hours)	DDF relationship	Design rainfall depths (mm)				
			P_{10}	P_{20}	P_{50}	P_{100}	P_{200}
A6H006	4.4	M&P/LEV1	71.5	88.2	114.7	141.2	158.8
		Hershfield	77.1	95.3	119.3	137.4	155.6
		RLMA&SI	72	83.8	100.3	113.5	127.5
B7H004	3.7	M&P/LEV1	112.2	138.5	180.1	221.6	249.3
		Hershfield	110.8	136.8	171.3	197.4	223.5
		RLMA&SI	94.6	112.4	148.8	160.8	185.3
C5H022	1.6	M&P/LEV1	61	75.3	97.8	120.4	135.4
		Hershfield	63.3	78.3	98.0	112.9	127.8
		RLMA&SI	49.9	57.8	68.8	77.6	86.9
G1H008	4	M&P/LEV1	49.2	60.7	78.9	97.1	109.3
		Hershfield	36.7	45.4	56.8	65.5	74.1
		RLMA&SI	41.2	46.2	52.6	57.4	62.1
H7H004	2.3	M&P/LEV1	27.6	34.1	44.3	54.6	61.4
		Hershfield	42.1	52.0	65.1	75.0	84.9
		RLMA&SI	49.3	59.6	74.7	87.5	101.6
W5H006	5	M&P/LEV1	98.3	121.3	157.7	194.1	218.4
		Hershfield	85.3	105.4	132.0	152.1	172.2
		RLMA&SI	82.4	98.0	120.8	140.1	161.4
X2H010	3.3	M&P/LEV1	130.1	160.7	208.9	257.0	289.2
		Hershfield	86.9	107.3	134.4	154.8	175.3
		RLMA&SI	82.3	97.8	120.5	139.8	161.1

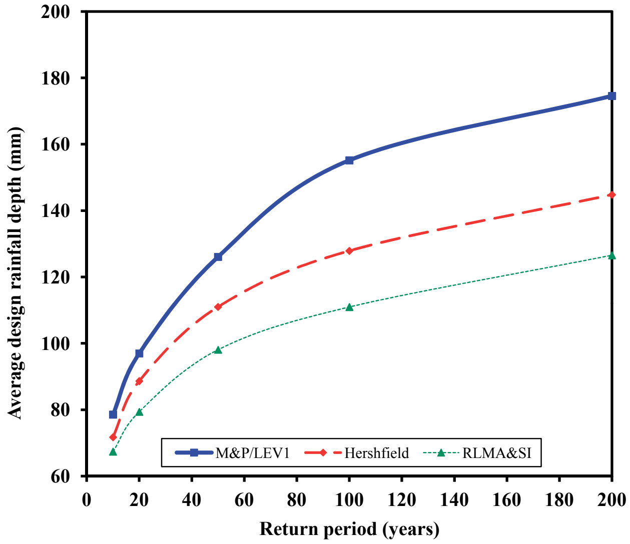

Figure 6
Average design rainfall depth: $T_c \leq 6$ h

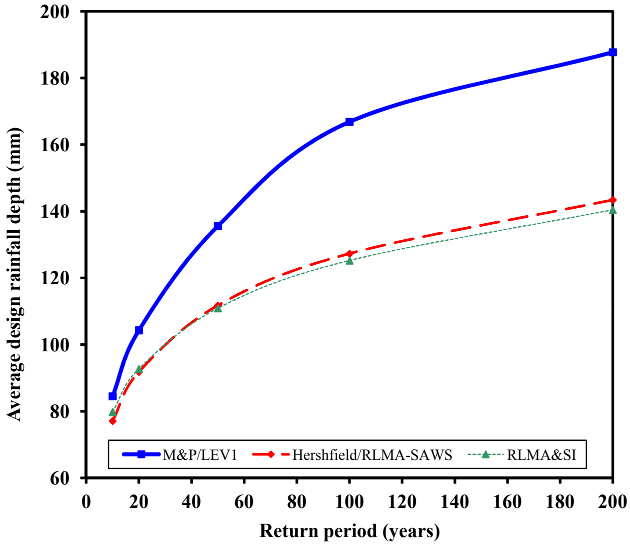

Figure 7
Average design rainfall depth: $6 < T_c \leq 24$ h

association was lower. The design rainfall depths based on the M&P/LEV1 relationship were overestimated for all of the return periods, in comparison to the linear interpolation between the modified Hershfield equation and the 1-day point rainfall depths from the RLMA-SAWS database and the RMLA&SI approach. However, the M&P/LEV1 relationship underestimated the 10- and 20-year design rainfall depths in Catchments A4H002, C5H012, C5H054, C5R001 and C5R003. As in the case of $T_C \leq 6$ h, a constant coefficient of determination ($r^2 = 0.53$) was evident between the M&P/LEV1 and Hershfield/RLMA-SAWS relationships. The comparison between the M&P/LEV1 and RLMA&SI relationships confirmed that the degree of association was similar, as in the latter case, although the r^2-values increased with an increase in return period. The Hershfield/RLMA-SAWS relationship overestimated the design rainfall depths for the full range of return periods under consideration, in comparison to the RLMA&SI relationship in 39% of the catchments. The design rainfall depths were also underestimated in 39% of the catchments, while the results in the remaining 22% of the catchments (A4H002, C5H003, C8H003 and Q1H001) were characterised by an almost perfect fit. The degree of association was acceptable; the r^2-values varied from 0.80 at the 10-year return period and decreased to 0.69 at the 200-year return period. Figure 7 is illustrative of the average design rainfall depths based on the 3 DDF relationships within the critical

Table 9
Design rainfall depths for 6 < T_c ≤ 24 hours

Catchment description	T_c (hours)	DDF relationship	Design rainfall depths (mm)				
			P_{10}	P_{20}	P_{50}	P_{100}	P_{200}
A2H012	18	M&P/LEV1	94.6	116.8	151.8	186.3	210.2
		Hershfield/RLMA-SAWS	81.3	97.6	120.6	138.2	158.9
		RLMA&SI	92.9	109.4	133.4	153.2	175.0
A4H002	18.1	M&P/LEV1	88.2	108.8	141.5	174.2	195.9
		Hershfield/RLMA-SAWS	92.6	109.8	133.3	151.8	171.0
		RLMA&SI	94.3	109.7	131.2	148.6	166.9
B4H003	19.6	M&P/LEV1	96.8	119.5	155.4	191.2	215.1
		Hershfield/RLMA-SAWS	75.2	88.2	105.6	119.3	133.4
		RLMA&SI	85.1	96.6	115.2	124.1	136.2
C5H003	18.3	M&P/LEV1	77.9	96.2	125.1	153.9	173.2
		Hershfield/RLMA-SAWS	78.5	93.0	112.7	128.0	143.8
		RLMA&SI	80.3	92.6	109.1	121.9	135.1
C5H008	11.9	M&P/LEV1	59.2	73.1	95.1	117.0	131.6
		Hershfield/RLMA-SAWS	71.0	86.1	106.2	121.6	137.3
		RLMA&SI	65.8	76.4	90.9	102.5	114.7
C5H012	20.2	M&P/LEV1	66.4	81.9	106.5	131.1	147.5
		Hershfield/RLMA-SAWS	70.5	82.7	99.1	111.8	124.8
		RLMA&SI	76.9	89.1	106.1	119.6	133.9
C5H054	16.9	M&P/LEV1	74.4	91.8	119.4	146.9	165.3
		Hershfield/RLMA-SAWS	79.8	94.7	114.6	130.0	145.5
		RLMA&SI	77.6	89.3	105.3	117.7	130.5
C5R001	21.3	M&P/LEV1	72.1	89.0	115.7	142.4	160.2
		Hershfield/RLMA-SAWS	73.4	85.8	102.7	115.9	129.6
		RLMA&SI	84.6	98.1	116.7	131.7	147.4
C5R003	13.9	M&P/LEV1	75.2	92.8	120.6	148.5	167.0
		Hershfield/RLMA-SAWS	80.5	96.8	118.8	135.7	152.9
		RLMA&SI	80.7	93.5	111.4	125.6	138.4
C8H003	19.2	M&P/LEV1	90.0	111.1	144.5	177.8	200.1
		Hershfield/RLMA-SAWS	79.0	92.4	110.3	124.2	138.4
		RLMA&SI	83.5	95.4	111.6	124.4	137.7
D1H001	19.9	M&P/LEV1	68.1	84.1	109.3	134.5	151.4
		Hershfield/RLMA-SAWS	68.5	79.7	94.7	106.2	117.8
		RLMA&SI	66.9	76.0	87.8	96.5	105.3
Q1H001	18	M&P/LEV1	53.5	66.0	85.8	105.6	118.8
		Hershfield/RLMA-SAWS	55.0	63.7	75.2	84.2	93.4
		RLMA&SI	54.7	63.2	74.7	83.9	93.1
Q9H004	6.3	M&P/LEV1	75.7	93.4	121.5	149.5	168.2
		Hershfield/RLMA-SAWS	67.0	82.7	103.5	119.2	134.9
		RLMA&SI	60.0	70.2	84.5	95.9	108.0
Q9H008	12.7	M&P/LEV1	88.9	109.8	142.7	175.6	197.6
		Hershfield/RLMA-SAWS	70.8	85.6	105.5	120.9	136.6
		RLMA&SI	63.9	74.8	89.9	102.1	114.9
R1H001	6.2	M&P/LEV1	91.8	113.3	147.3	181.3	204.0
		Hershfield/RLMA-SAWS	75.0	92.7	115.9	133.6	151.2
		RLMA&SI	62.2	72.8	87.5	99.3	111.9
T3H004	18.8	M&P/LEV1	103.9	128.3	166.7	205.2	230.9
		Hershfield/RLMA-SAWS	87.8	104.1	126.6	144.5	163.1
		RLMA&SI	97.6	115.1	140.2	161.3	184.4
V2H002	18.9	M&P/LEV1	133.1	164.4	213.7	263.0	295.9
		Hershfield/RLMA-SAWS	86.5	102.5	124.7	142.3	160.7
		RLMA&SI	98.7	115.1	138.0	156.7	176.7
W5H005	17.8	M&P/LEV1	110.9	136.9	178.0	219.1	246.5
		Hershfield/RLMA-SAWS	95.0	114.4	141.7	164.1	187.9
		RLMA&SI	111.3	132.3	162.9	189.0	217.7

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Table 10 Design rainfall depths for 24 < T_C ≤ 168 hours							
Catchment description	**T_C (hours)**	**DDF relationship**	**Design rainfall depth (mm)**				
			P_{10}	**P_{20}**	**P_{50}**	**P_{100}**	**P_{200}**
C3H003	78	M&P/LEV1	89.7	110.7	144.0	177.2	199.3
		RLMA-SAWS	113.6	129.6	150.2	165.5	180.7
		RLMA&SI	110.0	127.1	149.8	167.7	184.9
C4H001	34	M&P/LEV1	86.6	106.9	139.0	171.1	192.5
		RLMA-SAWS	93.7	108.5	128.8	144.9	161.9
		RLMA&SI	92.1	106.1	125.1	139.7	154.7
C4H002	111	M&P/LEV1	95.9	118.4	153.9	189.4	213.1
		RLMA-SAWS	130.3	149.5	175.2	195.2	215.6
		RLMA&SI	123.2	142.1	167.6	188.7	209.8
C5H015	43	M&P/LEV1	82.6	102.0	132.6	163.2	183.6
		RLMA-SAWS	93.0	107.3	126.7	141.9	157.7
		RLMA&SI	93.3	107.5	126.9	141.5	157.0
C5H016	111.1	M&P/LEV1	79.5	98.1	127.6	157.0	176.6
		RLMA-SAWS	110.9	129.7	156.1	177.4	200.0
		RLMA&SI	107.0	123.3	145.3	162.4	180.0
C5H018	99.6	M&P/LEV1	83.0	102.5	133.2	163.9	184.4
		RLMA-SAWS	111.5	129.3	153.5	172.7	192.7
		RLMA&SI	115.1	132.7	156.1	174.2	192.9
C5R002	50.5	M&P/LEV1	71.1	87.7	114.0	140.4	157.9
		RLMA-SAWS	87.5	101.5	120.4	135.3	150.7
		RLMA&SI	84.5	98.0	116.6	131.6	147.3
C5R004	47.9	M&P/LEV1	83.7	103.4	134.4	165.4	186.0
		RLMA-SAWS	97.0	111.9	132.0	147.8	164.2
		RLMA&SI	90.2	103.9	122.4	136.8	151.7
C8H001	122	M&P/LEV1	117.7	145.3	188.9	232.4	261.5
		RLMA-SAWS	126.6	141.0	159	172.1	184.7
		RLMA&SI	131.8	152.5	179.3	201.3	224.5
D2H001	106	M&P/LEV1	124.8	154.1	200.3	246.5	277.3
		RLMA-SAWS	111.0	127.2	149.2	166.2	183.6
		RLMA&SI	117.7	136.7	162.2	183.4	205.6
D1H005	60	M&P/LEV1	104.8	129.4	168.3	207.1	233.0
		RLMA-SAWS	91.3	106.0	126.7	143.6	161.7
		RLMA&SI	101.4	118.8	142.2	161.4	182.4
E2H003	59	M&P/LEV1	47.0	58.1	75.5	92.9	104.5
		RLMA-SAWS	71.0	82.0	96.5	107.3	118.3
		RLMA&SI	54.9	63.1	74.3	82.6	91.5
Q7H003	59	M&P/LEV1	64.1	79.1	102.9	126.6	142.4
		RLMA-SAWS	70.8	81.8	96.5	107.8	119.2
		RLMA&SI	82.1	95.1	112.5	126.0	139.9
Q9H010	108	M&P/LEV1	74.6	92.1	119.7	147.4	165.8
		RLMA-SAWS	82.6	95.5	112.6	125.8	139.1
		RLMA&SI	94.0	108.8	128.7	144.2	160.1
Q9H012	85	M&P/LEV1	68.0	83.9	109.1	134.2	151.0
		RLMA-SAWS	77.9	90.1	106.3	118.8	131.4
		RLMA&SI	89.1	103.2	122.1	136.8	151.9
V6H002	48	M&P/LEV1	128.7	158.9	206.5	254.2	286.0
		RLMA-SAWS	125.6	142.8	165.3	182.4	199.5
		RLMA&SI	129.2	148.1	173.5	193.1	213.4

storm duration range, 6 < T_C ≤ 24 h for all of the catchments listed in Table 9.

The results in Table 10 (24 < T_C ≤ 168 h) indicated that the M&P/LEV1 relationship overestimated the design rainfall depths for the 50-, 100- and 200-year return periods up to a critical storm duration of 50 h, compared to the linear interpolated RLMA-SAWS *n*-day design point rainfall depths and the RLMA&SI approach. All of the design rainfall depths with critical storm durations of or exceeding 100 h were underestimated, except in Catchments C8H001, D2H001 and Q9H012. In Catchment D2H001 all of the design rainfall depths were overestimated, while only the 50-, 100- and 200-year return periods were overestimated in the other 2 catchments.

The degree of association between these methods was low, since the coefficient of determination varied between 0.60 (10-year) and decreased to 0.49 (200-year), in the case of the

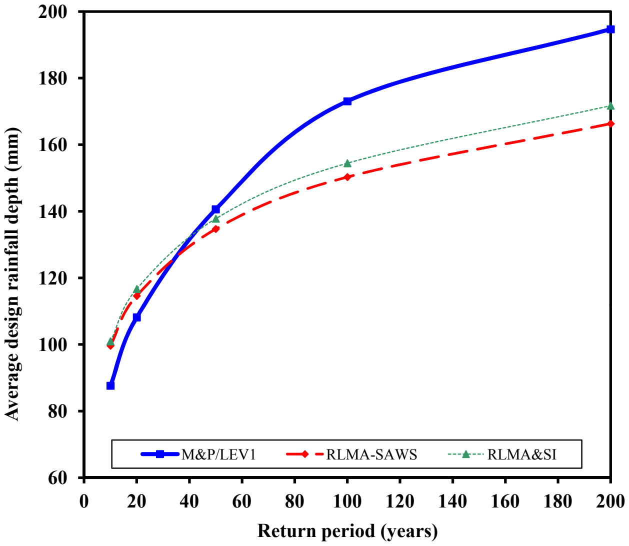

Figure 8
Average design rainfall depth: 24 < T_C ≤ 168 h

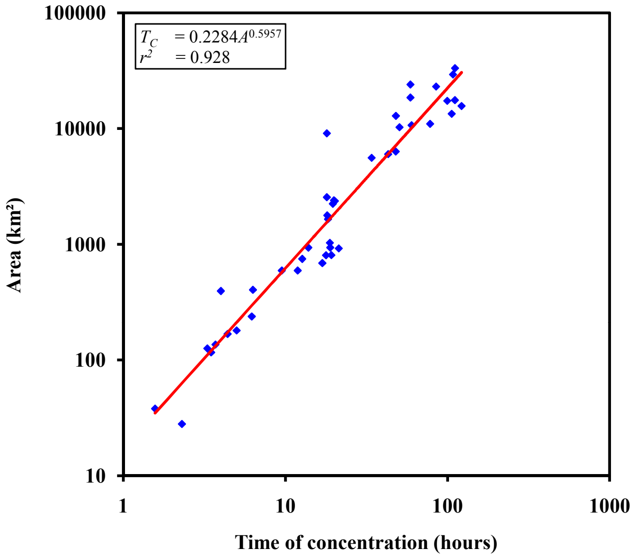

Figure 9
ARF: Area versus time of concentration power-law curve

M&P/LEV1 and RLMA-SAWS comparison, while in the case of the M&P/LEV1 and RMLA&SI comparison the coefficient of determination varied between 0.75 (10-year) and increased to 0.77 at the 200-year return period. The comparison between the RLMA&SI and the linear-interpolated RLMA-SAWS *n*-day design point rainfall depths were characterised by a high degree of association; the coefficient of determination varied between 0.85 at the 10-year return period and decreased to 0.72 at the 200-year return period. Figure 8 is illustrative of the average design rainfall depths based on the 3 DDF relationships within the critical storm duration range, 24 < T_C ≤ 168 h for all of the catchments listed in Table 10.

In the methodology it was highlighted that the RLMA&SI gridded design point rainfall values were converted into average catchment values by using a 4-step process. In order to establish the applicability thereof, the RLMA&SI design rainfall depth results in 4 of the 29 secondary study areas were compared to the results obtained by Parak and Pegram (2006).

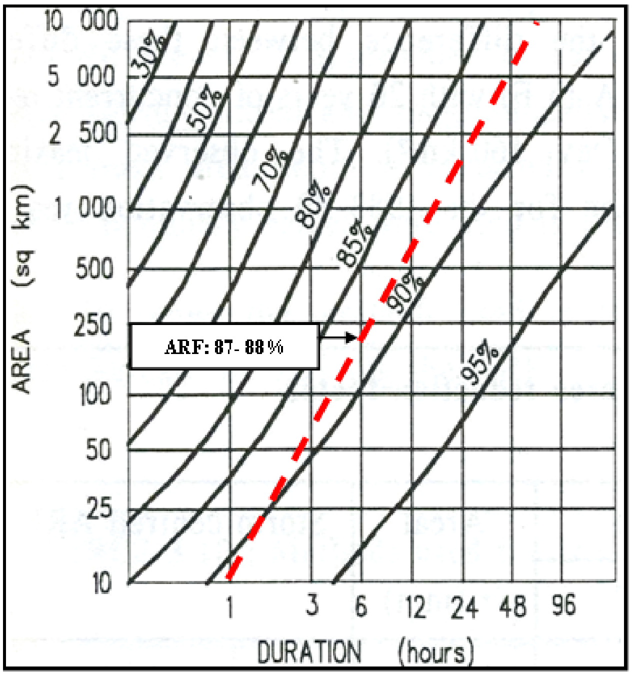

Figure 10
ARF diagram derived from fixed storm data (NERC, 1975; as cited in Alexander, 1990)

The catchments used for these comparisons were: Q7H003, Q9H010, Q9H012 and V6H002. In these catchments, the design rainfall estimates by Parak and Pegram (2006) differed with between 25% (10-year) and 34% (200-year) from this study; compared to the M&P/LEV1 and RLMA-SAWS estimates, the differences varied between 26% and 56%. These differences might be ascribed to the fact that Parak and Pegram (2006) followed a different approach to averaging the design rainfall depths. They chose a number of locations (depending on the size of the catchment) along the main watercourse within the catchment, for which design rainfall depth estimates based on the RLMA&SI approach were then obtained. The average depth for each catchment was determined, and thereafter the intensity, duration and frequency relationships were derived by fitting a simple power-law function of storm duration (T_C) to the average design rainfall depths. At the 10- to 200-year return periods, their average rainfall depths and intensities were expressed in the form of Eqs. (13) and (14):

$$P = aT_C^{\,b} \tag{13}$$

$$I = aT_C^{\,-c} \tag{14}$$

where:

a, b, c = fitted power-law parameters, with c = b-1
I = average rainfall intensity (mm·h^{-1})
P = average rainfall depth (mm)
T_C = time of concentration (h)

Areal reduction factors

The T_C values were plotted against the associated catchment areas on a double log graph and a straight line fit represented by a power function was fitted through the data points. Eq. (12) is represented by a power function equal to the 1:1 trend line;

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Table 11 Comparison of ARF results: Eqs. (12) and (16)				
Catchment description	Area (km²)	T_C (hours)	ARF (%)	
			Eq. (12)	Eq. (16)
A2H012	2 551	18.0	80.6	82.2
A4H002	1 777	18.1	83.1	83.5
A6H006	168	4.4	91.1	91.5
B4H003	2 240	19.6	81.9	82.7
B7H004	136	3.7	91.6	92.2
C3H003	10 990	78.0	78.1	76.5
C4H001	5 590	34.0	78.4	79.2
C4H002	17 599	111	76.6	74.5
C5H003	1 650	18.3	83.6	83.8
C5H008	593	11.9	88.1	87.4
C5H012	2 366.3	20.2	81.7	82.5
C5H015	6 009	43.0	79.2	78.9
C5H016	33 277.2	111.1	71.5	71.6
C5H018	17 360.3	99.6	76.1	74.5
C5H022	38	1.6	95.1	96.1
C5H054	687.8	16.9	88.8	86.9
C5R001	921.5	21.3	88.2	85.9
C5R002	10 259.9	50.5	76.1	76.7
C5R003	936.7	13.9	86.0	85.8
C5R004	6 330.9	47.9	79.4	78.7
C5R005	116.4	3.5	92.2	92.7
C8H001	15 673	122.0	78.1	75.0
C8H003	806	19.2	88.5	86.3
D1H001	2 397	19.9	81.5	82.4
D1H005	10 680	60.0	76.8	76.6
D2H001	13 421	106.0	78.4	75.6
E2H003	24 044	59.0	70.1	73.1
G1H008	395	4.0	85.4	88.8
H3H001	593	9.5	87.0	87.4
H7H004	28	2.3	98.3	97.0
Q1H001	9 091	18.0	70.7	77.2
Q7H003	18 534	59.0	72.4	74.2
Q9H004	404	6.3	87.5	88.7
Q9H008	748	12.7	87.0	86.6
Q9H010	29 328	108.0	72.4	72.2
Q9H012	23 067	85.0	72.9	73.3
R1H001	238	6.2	90.6	90.4
T3H004	1 029	18.8	86.9	85.5
V2H002	937	18.9	87.5	85.8
V6H002	12 862	48.0	74.1	75.8
W5H005	804	17.8	88.1	86.3
W5H006	180	5.0	91.3	91.3
X2H010	126	3.3	91.5	92.4

in other words, the coefficient of determination equals unity. The results also showed a high degree of association between Eq. (15a) and the clustered points, with the r^2-value equal to 0.93. The power-law relationship associated with this r^2 value can alternatively also be expressed as Eq. (15b), which provides a good indication of T_C associated with any catchment area under consideration. Eq. (16) resulted from the substitution and simplification of Eq. (15b) into Eq. (12).

$$A = 17.1208 T_C^{\,1.5571} \quad (15a)$$

$$T_C = 0.2284 A^{\,0.5957} \quad (15b)$$

$$ARF = \left(-6\ 944.3 \ln A + 115\ 731.9\right)^{0.4} \quad (16)$$

where:
A = catchment area (km²)
ARF = areal reduction factor (%)
T_C = time of concentration (h)

A summary of the applicable results is shown in Table 11, and Fig. 9 illustrates the fitted power-law relationship.

Figure 10 represents the ARF diagram published in the UK FSR (NERC, 1975) with Fig. 9, the area-duration power-law curve, superimposed thereon. It is clearly evident that this power-law curve yielded a constant ARF, of between 87% and 88%, across the ARF diagram, for durations exceeding 3 h. This implies that, for the catchments under consideration, the ARFs for design point rainfall depths with durations equal to T_C in a specific catchment appear to be fairly constant between 87% and 88%. Similar results were obtained by Pegram (2003), although Eq. (15b) differed slightly.

Days of thunder per year

Figures 11 and 12 served as a confirmation that there is no direct relationship between the *R* and *M*-values of the rainfall stations under consideration, as originally anticipated.

The data points in these figures were randomly scattered around a curve to which a third-order polynomial relationship could not even be fitted satisfactorily, especially in the case of the Type 3 and/or 4 storm distributions. The degree of association between the *R* and *M*-values of the Type 1 and/or 2 storm distributions was higher compared to that of the Type 3 and/or 4 storm distributions, emphasising the more uniform areal and temporal distribution of rainfall, and associated lower occurrence of thunder, typical of the winter and/or coastal rainfall regions.

Conclusions and recommendations

Averaging of rainfall depth

The Thiessen polygon and isohyetal methods are the preferred methods to determine average areal design rainfall depths; especially where rainfall stations have a poor areal distribution and the catchment topography is highly variable. However, the isohyetal method requires much more data manipulation in an ArcGIS™ environment with longer associated computation times. The Thiessen polygon method is therefore recommended for future use.

Critical storm duration rainfall

On average, the M&P/LEV1 relationship estimated the largest design rainfall depths for all of the return periods and critical storm duration ranges under consideration, except for the 10- and 20-year return periods of the $24 < T_C \leq 168$ h range. The Hershfield/RLMA-SAWS relationship estimated the second-highest design rainfall depths for the full range of return periods of the $T_C \leq 6$ h and $6 < T_C \leq 24$ h ranges. On average, the lowest design rainfall depths were estimated by the RLMA&SI relationship, except in individual cases where the critical storm

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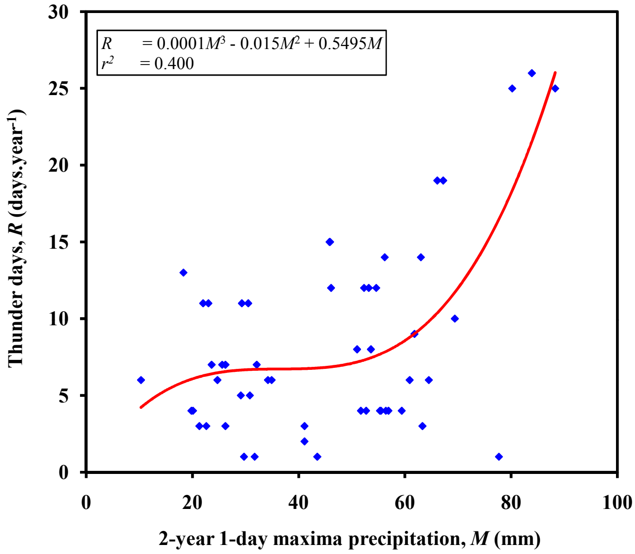

Figure 11
R versus M-values for stations with Type 1 and/or 2 storm distributions

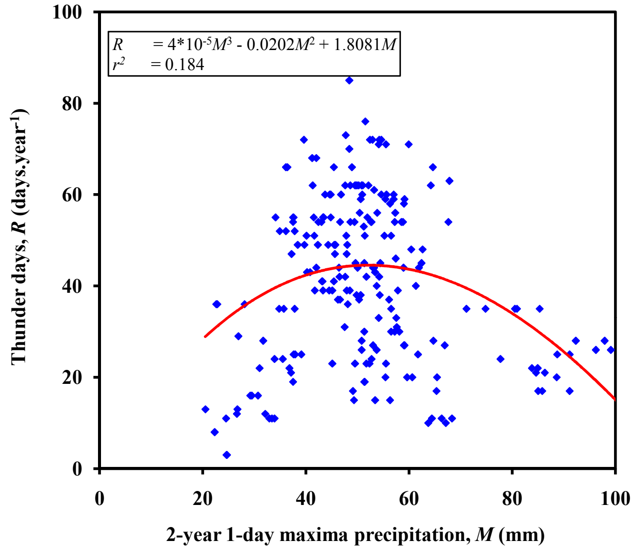

Figure 12
R versus M-values for stations with Type 3 and/or 4 storm distributions

duration exceeded 100 h. Here, it resulted in higher estimates compared to those of the other 2 DDF relationships. However, in 57% of the catchments with $T_C \leq 100$ h at the 200-year return period, the M&P/LEV1 relationship provided more accurate estimates.

On average, these different DDF relationships demonstrated a high degree of association amongst each other, with r^2-values ranging from 0.71 to 0.93 for critical storm durations less than 6 h. The critical storm durations ranging between 6 and 24 h were characterised by constant r^2-values of 0.53 between the M&P/LEV1 and Hershfield/RLMA-SAWS relationships, while the degree of association between the Hershfield/RLMA-SAWS and RLMA&SI relationships decreased with an increase in return period. The critical storm durations ranging between 24 and 168 h were characterised by an acceptable to high degree of association between all of the methods. The results also showed a tendency to decrease in association with an increase in return period.

Since all of these DDF relationships, except for the RMLA&SI approach, are currently widely used as standard rainfall input information to the deterministic flood estimation methods used in South Africa, the question arises whether this must remain as the standard procedure. Based on the results obtained from this study, it is recommended that the M&P/LEV1 and Hershfield DDF relationships should be seen as conservative estimates and their use should be limited to small catchments ($T_C \leq 6$ h). However, the Hershfield/RLMA-SAWS relationship proved to be more reliable in medium-sized catchments ($6 < T_C \leq 24$ h). The RMLA&SI approach must be used as the standard DDF relationship for all of the critical storm durations under consideration, since it utilises the scale invariance of growth curves with duration, and the Java-based software with graphical interface enables reliable and consistent design rainfall estimation in South Africa. In addition, by implementing this, the current M&P/LEV1 relationship, which depends heavily on averaged regional conditions, and the Hershfield relationship, with the highly variable and questionable parameter – the average number of thunder days per year, can be excluded from the calculation procedures.

Areal reduction factors

Eq. (15b) can be satisfactorily used to determine T_C associated with any catchment area under consideration in the study areas. In addition, the simplified ARF relationship expressed by Eq. (16) can be used instead of Eq. (12) to convert design point rainfall depths or intensities to average areal design rainfall depths or intensities in the identified catchments. However, the validity of both Eqs. (15b) and (16) must be further tested, improved and verified to be acceptable for general use on a national scale in South Africa.

Days of thunder per year

There was no clear relationship between the average numbers of days per year on which thunder was heard *(R)* and the 2-year mean of the annual daily maxima rainfall *(M)* values. The number of thunder days per year is not only influenced by the temporal distribution of storms; the climate, type of rainfall, areal distribution of rainfall, location, altitude above mean sea level and topography must be taken into consideration.

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