

Development of Appropriate Synthetic Design Storms for Small Catchments in Gauteng, South Africa

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ABSTRACT

Synthetic design storms are often used as input in dynamic rainfall-runoff simulation models. A number of methods to generate synthetic design storms are described in the literature. However, the selection of an inappropriate synthetic design storm will generate unrealistic simulations. Therefore, the aim of this study was to develop appropriate synthetic design storms for small urban catchments in Gauteng, South Africa. This study evaluated the applicability of the SCS method adapted for South Africa (SCS-SA), the Chicago Design Storm method and the Rectangular Hyetograph method. The performance of each method was evaluated compared to observed rainstorm events. Storm shape and intensity were used for the evaluation. As expected, the Rectangular Hyetograph was the least representative of naturally occurring storm events. The Chicago Design Storm and SCS-SA distribution curves initially performed poorly. Adjustment of the timing of the peak storm intensity to the start of the event resulted in a significant improvement for both methods. A novel approach was used to generate intermediate site-specific SCS-SA rainfall distribution curves anywhere in the study area.

1. INTRODUCTION

1.1 Background

A natural hydrological event, in its simplest form, starts with a rainstorm event (hyetograph) and ends with runoff (hydrograph), both having unique and quantifiable characteristics. For the rainstorm event, this includes the hyetograph shape and temporal distribution of rainfall intensity. The subsequent runoff has characteristics including hydrograph shape, runoff volume,

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and peak discharge (Adams and Howard 1986; Na and Yoo 2018). The catchment, with its various physical characteristics and antecedent moisture conditions, determines the relationship between the hyetograph and hydrograph (Massari et al. 2023).

Despite the uncertainties about this transformation of the hyetograph into a hydrograph, in stormwater modeling, it is generally assumed in the widely used single event modeling approaches (e.g. Rational and SCS methods) that their return periods are identical (Adams and Howard 1986). Synthetic design storms, together with Intensity-Duration-Frequency (IDF) curves, are used extensively internationally in many urban stormwater designs and studies (Balbastre-Soldevila et al. 2019).

Observed flow data are generally not widely available. In the case of a new stormwater network, observed flow data does not usually exist. Observed sub-daily short time step rainfall data will provide the next best information when used in a continuous simulation (Winter et al. 2019; Grimaldi et al. 2021). However, with the limited availability of short time step rainfall data, designers generally revert to single event-based simulation modeling using a synthetic design storm as input. Therefore, synthetic design storms have an important role to play in the design and assessment of urban stormwater networks.

The hydrological and hydraulic behaviour of an urban stormwater drainage network is complex. Sophisticated computer-aided rainfall-runoff simulation modeling is often used to simulate this complexity. The rainfall-runoff process can be simulated effectively and accurately using software such as Stormwater Management Model (SWMM) developed by the United States Environmental Protection Agency (EPA). This software has become the preferred method in the United States and Canada (Watt and Marsalek 2013) and is also widely used in South Africa (City of Cape Town Development Service 2002; Barnard et al. 2019; Brooker et al. 2023). The selection of an inappropriate synthetic design storm will, however, generate unrealistic runoff results (Watt and Marsalek 2013).

1.2 Relevant design storm methods

Several methods to generate synthetic design storms are used in South Africa and internationally, as reviewed by Veneziano and Villani (1999); Al-Saadi (2002); Asquith et al. (2003); Prodanovic and Simonovic (2004); Smith (2004); Knoesen (2005); Watt and Marsalek (2013); Pan et al. (2017); Weesakul et al. (2017); Ramlall (2020); and Wartalska et al. (2020).

This study focuses on the Chicago Design Storm (CDS) method developed by Keifer and Chu (1957); the United States Department of Agriculture's Soil Conservation Services (SCS) synthetic storm distribution curves (SCS 1973), adapted for Southern African conditions (SCS-SA) by Schulze (1984); and the Rectangular hyetograph (REC) method, commonly associated with the Rational method developed by Mulvaney (1851). These methods are broadly categorised by Veneziano and Villani (1999) as methods associated with IDF curves, but the derivation of a synthetic design storm distribution for each method from the IDF curves is different.

The Rational method makes use of a single point on the IDF curve and assumes it remains unchanged during the rainstorm event, viz a rectangular shaped hyetograph. The peak discharge occurs when the duration of the rainstorm event is equal to the time of concentration of the catchment (Mulvaney 1851, cited by Dooge 1974), called the critical duration. If the duration of the REC is less than the critical duration, then the runoff from the entire catchment

has not yet reached the outlet point. Conversely, if the duration exceeds the critical duration, the intensity of the REC will be lower and, therefore, produce a lower peak discharge. Because of the uncertainty in the estimation of the time of concentration, the critical duration is found through the simulation of multiple RECs, starting at a short duration, and systematically increasing the duration until the discharge has reached a maximum.

In contrast to using a single point, the CDS method uses the full IDF curve. The shape of the IDF curve is approximated using the Sherman (1931) formula presented as Equation 1.

$$i_{av} = \frac{a}{(b+t)^c} \quad (1)$$

Where:

- i_{av} = average rainfall intensity for a particular storm duration (mm/hour),
- a, b, c = site specific constants, and
- t = storm duration (min).

The Sherman formula was manipulated, differentiated, and an advancement coefficient introduced to define the position of the peak intensity, relative to the total duration of the rainstorm event. This led to the development of the intensity distribution formulae. The formulae were subsequently integrated to develop cumulative rainfall distribution formulae presented in Equations 2 and 3 (Keifer and Chu 1957; Watson 1981; Smith 2004; Silveira 2016).

$$P_b = r \cdot P - \frac{t_b \cdot a}{60 \cdot \left(b + \frac{t_b}{r}\right)^c} \quad (2)$$

$$P_a = r \cdot P + \frac{a(t_a - T_p)}{60 \cdot \left(b + \frac{t_a - T_p}{1-r}\right)^c} \quad (3)$$

Where:

- P = total rainfall depth (mm),
- r = storm advancement coefficient,
- P_a = cumulative rainfall depth after the peak intensity (mm),
- P_b = cumulative rainfall depth before the peak intensity (mm),
- T_p = time when peak intensity occurs (min),
- t_a = duration from the peak intensity to the end of the event (min),
and
- t_b = duration from the start of the event to the peak intensity (min).

The standard SCS temporal distribution curves, Types I and II, were developed from the short duration design rainfall obtained from the United States Weather Bureau technical papers (U.S. Weather Bureau 1961). The depths were plotted against the duration for several locations and a curve was selected with the best fit (SCS 1973). The SCS Type I and II curves were originally adopted for use in South Africa (Schulze and Arnold 1979) but were later revised by Schulze (1984). Symmetrical curves were created based on the selection of four D-hour to 24-hour ratio

range classes. The four types of ratios and range classes for durations up to 3-hours that were selected by Schulze (1984) are depicted in Figure 1.

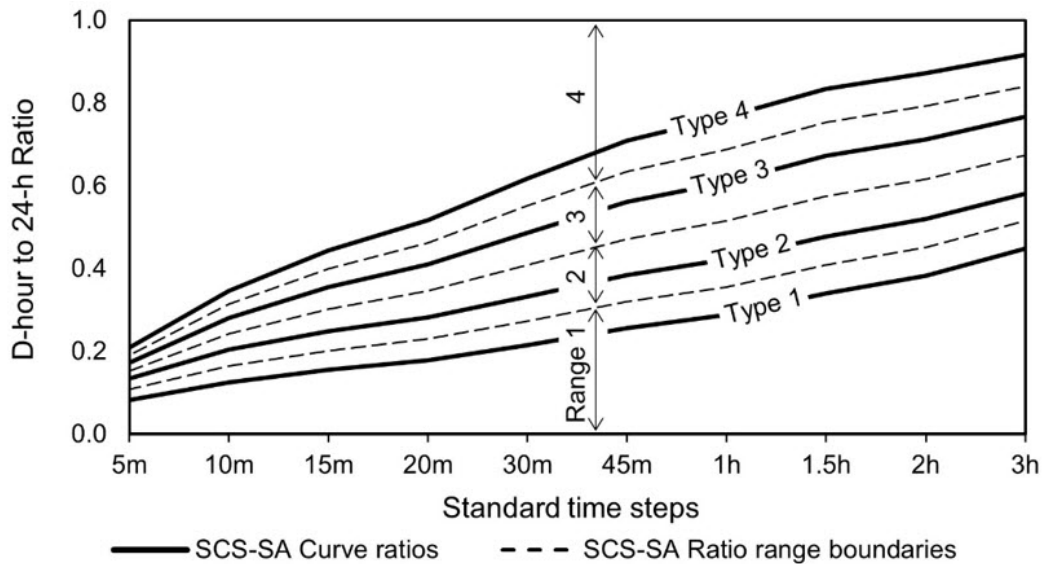


Figure 1 SCS-SA ratios and range classes.

The 5-min ratios of each type were positioned hypothetically at the centre of a 24-hour rainstorm event, and the ratio differences of increasing durations were divided equally on both sides of the 5-min ratio. The ratios were accumulated from the start to the end of 24-hours to form the four cumulative mass curves, which became known as the SCS-SA synthetic storm distribution curves Type 1 to 4 (Weddepohl 1988), as depicted in Figure 2.

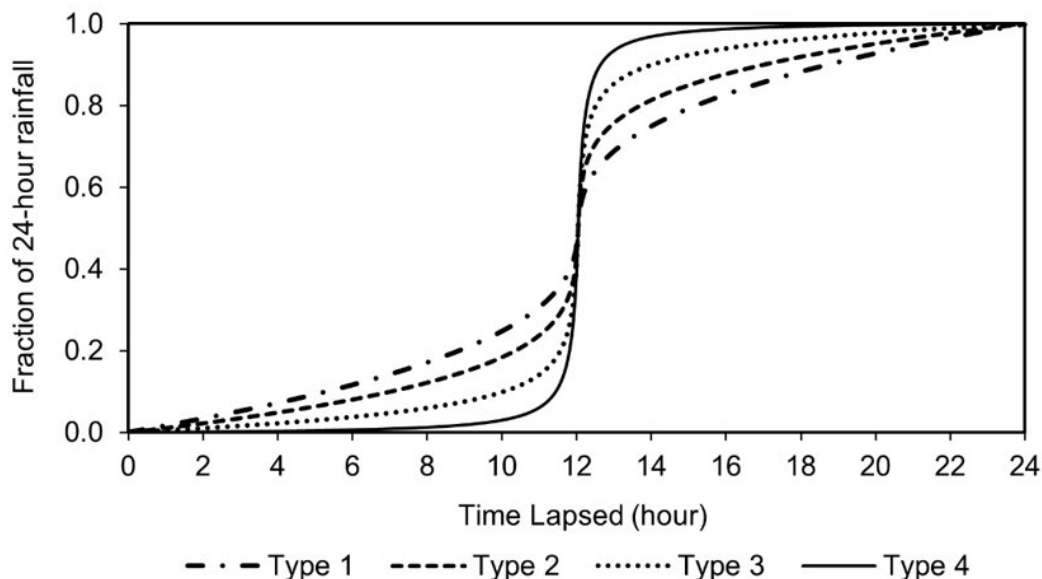


Figure 2 Time distributions of accumulated rainfall depth divided by total rainfall depths (Schmidt and Schulze 1987).

Weddepohl (1988) then determined the D-hour to 24-hour ratios using the at-site design rainfall for 40 autographic rainfall stations in South Africa and assigned each station to an appropriate ratio type considering the range applicable to each type. Weddepohl (1988) interpolated the

results geographically by linear interpolation to create a map that represents the regionalization of the four curves as depicted in Figure 3.

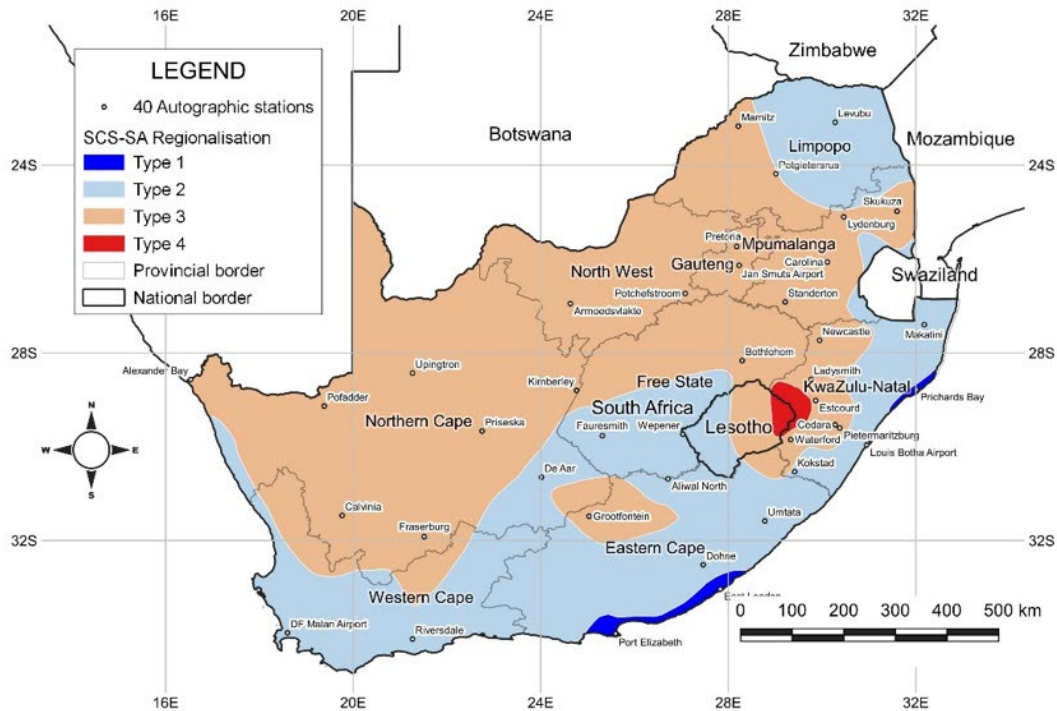


Figure 3 Regionalization of synthetic rainfall distributions in southern Africa (after Weddepohl 1988).

1.3 Study objective

Since the completion of Weddepohl’s study, with limited data in 1988, the South African Weather Service (SAWS) has installed numerous automatic rain gauges at strategic locations across the country. Many of these stations are in the Gauteng Province, which has the highest population density in South Africa, at about 15.1 million (StatsSA 2022). As such, the province continues to experience development of residential, commercial, and industrial properties. The stormwater management for these developments is generally planned using SWMM (Barnard et al. 2019; Brooker et al. 2023) or similar modeling software. However, a recent survey (Mouton et al. 2022) established that designers tend to use the design storm method with which they are most comfortable, rather than using observed data as guidance. As a result, the need to develop appropriate synthetic design storms for this province was identified.

The aim of this study was to develop appropriate synthetic design storms for small catchments in Gauteng, South Africa. The ability of synthetic design storms to mimic observed rainstorm events was tested. The timing of the peak intensity of the CDS and SCS-SA design storm was evaluated against advancement coefficients recommended in the literature. A novel approach was followed to develop intermediate SCS-SA curves for the study area.

2. METHODOLOGY

The methodology followed in this study included data checking, extraction of the Annual Maximum Series (AMS), extracting significant storm events and determining their storm parameters, assessment of storm shapes and intensities, and development of design storms. The rainfall data sets as obtained from the SAWS were processed for this study using a Java application called Rain-Pro (Munro 2021). Subsequent analyses of the data were done using Microsoft Excel. The process is summarised in Figure 4. Detailed discussions of the different steps follow in subsequent paragraphs.

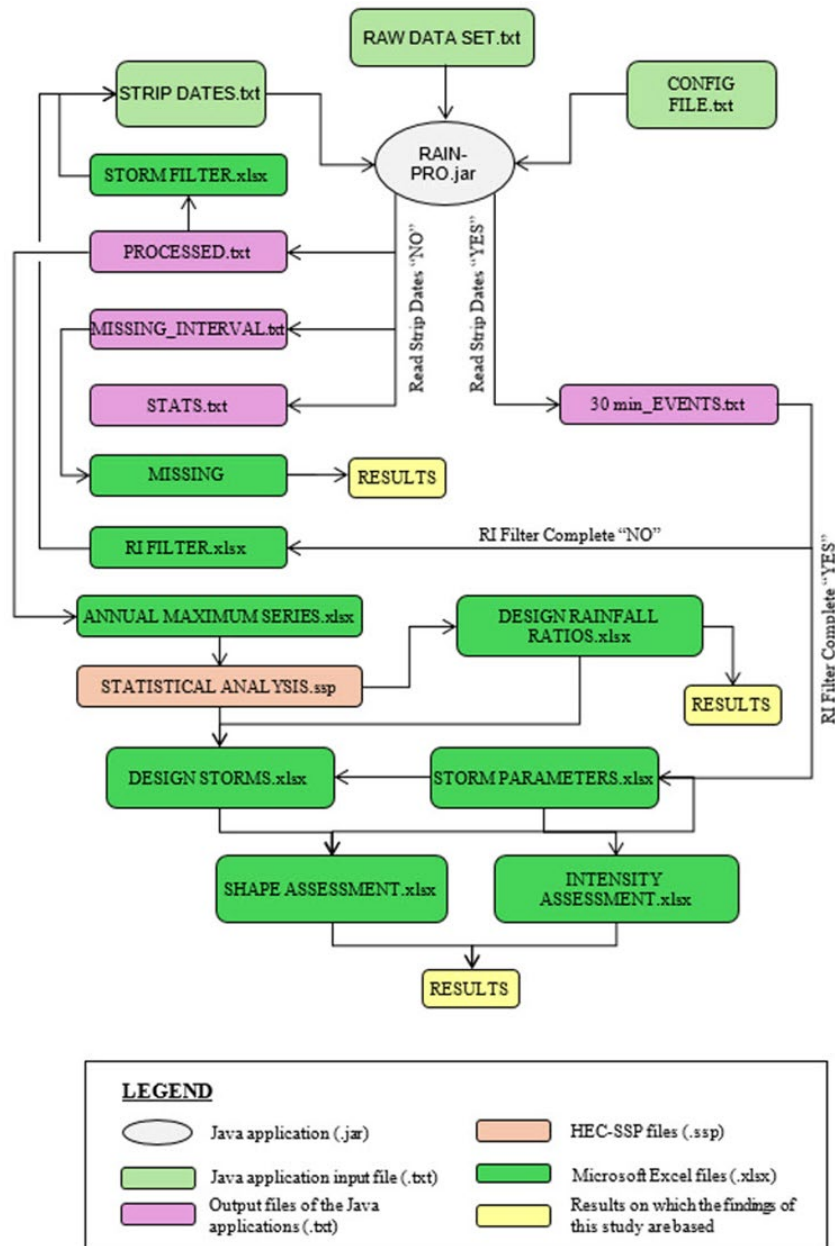


Figure 4 Process flow diagram followed in this study.

2.1 Study area

The Gauteng Province is the smallest of South Africa's provinces, but also the most densely populated (StatsSA 2022). The land cover in the province consists mainly of urban and agricultural land, as shown in Figure 5 (Geoterraimage 2021). The natural landcover is grasslands in the south and bushveld in the north (Geoterraimage 2021). It is located in the inland highveld region, with elevations ranging from 950 meters above mean sea level (mamsl) in the north to 1890 mamsl in the south, as shown in Figure 6 (NGI 2020). It is clear from Figure 6 that there are no major mountain ranges in the province.

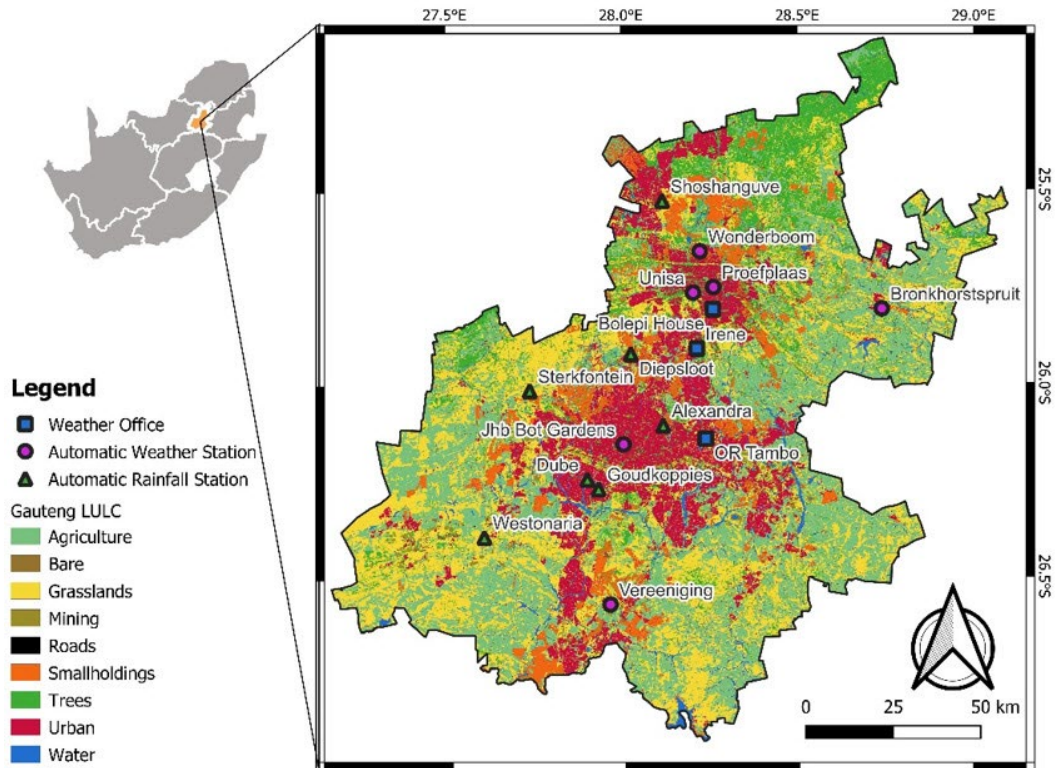


Figure 5 Gauteng land use and land cover (LULC) map (Geoterraimage 2021).

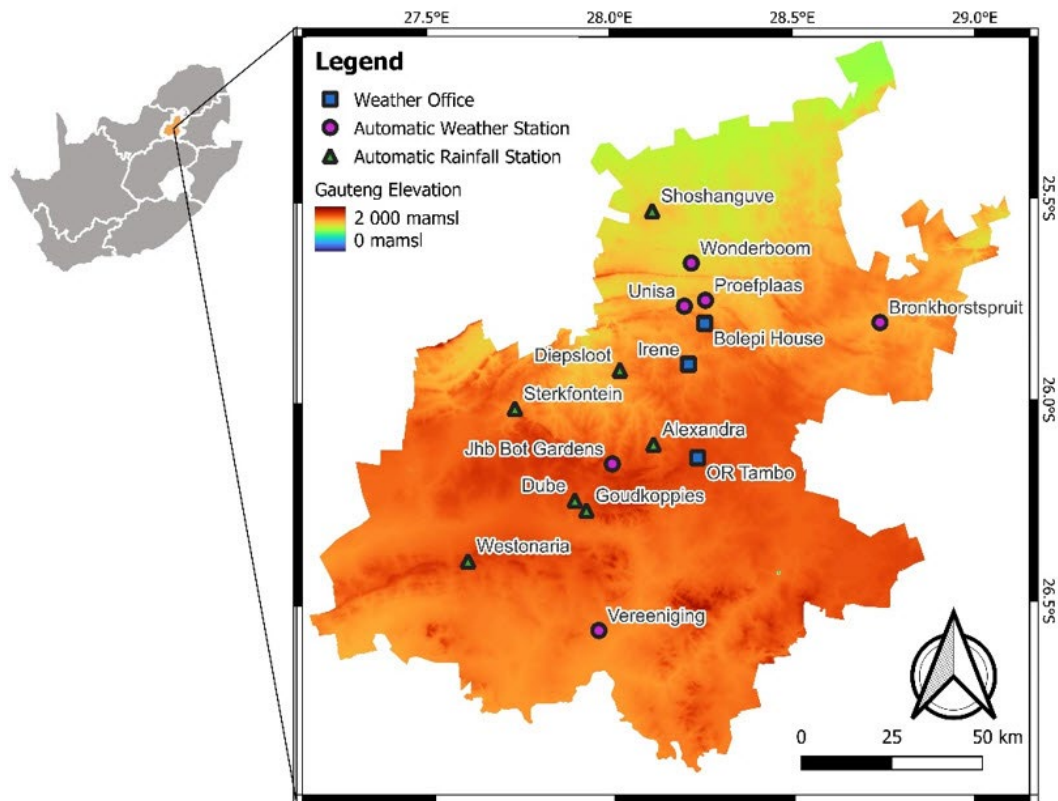


Figure 6 Gauteng elevation map (NGI 2020).

2.2 Data collation

Rainfall data were obtained from the SAWS database for 35 stations in the Gauteng Province. The rainfall is recorded in 5-min intervals using tipping bucket rain gauges with a rainfall resolution of 0.2 mm. The rain gauges are equipped with data loggers which continuously record data. The data is downloaded daily and goes through several quality checks before it gets uploaded into the SAWS database (Linnerts 2022). The rainfall data sets were further processed for this study using a Java application called Rain-Pro developed by Munro (2021).

From the 35 stations that were assessed, nineteen were omitted by Mouton et al. (2022), and subsequently from this study. The data quality of the stations was characterised depending on the data period and the percentage of missing data periods during wet months. Based on an average monthly rainfall analysis of the two stations with the longest records (Irene and OR Tambo), the months of October to April were considered wet months. The Irene and OR Tambo stations were considered reliable stations because of their long data periods (27 years) and minimal missing data (<2%). The Vereeniging, Johannesburg Botanical (Jhb Bot) Gardens, and Unisa stations also have long data periods (27 years), but with more missing data (<6%). The data periods of the remainder of the selected stations are more than ten years with less than 20% missing data. Omitted stations included those with data periods of less than ten years, or missing data periods of more than 20%. The sixteen stations that were used in subsequent analyses are depicted in Figure 7.

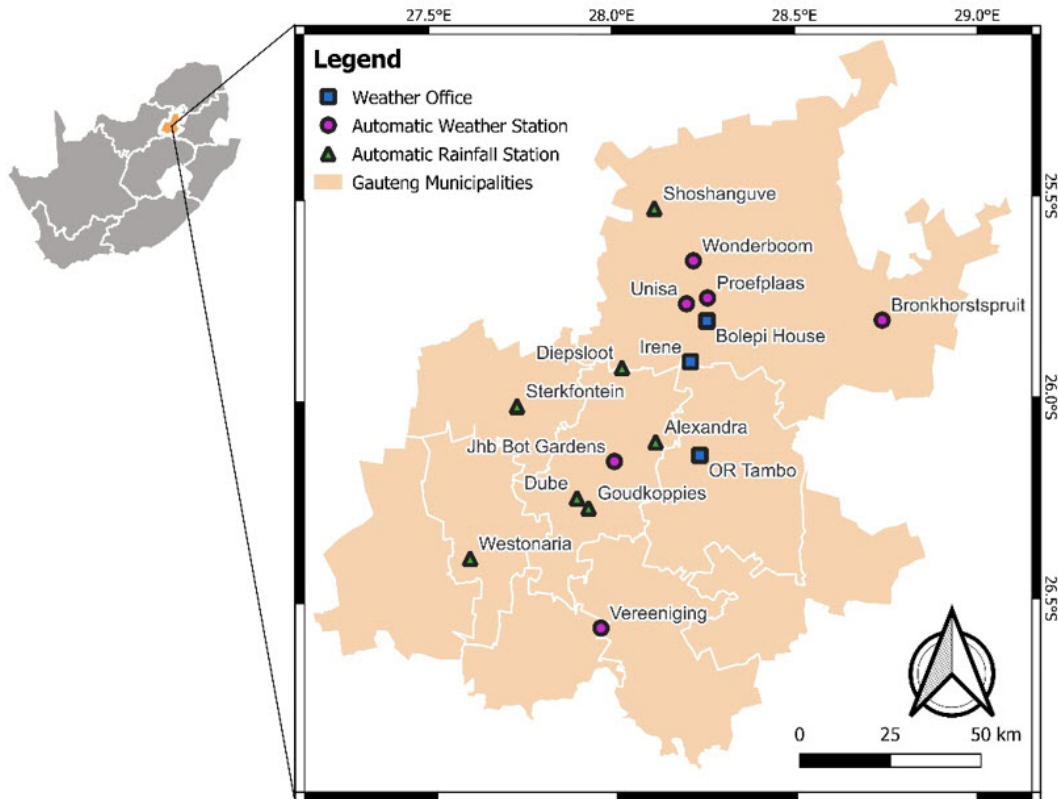


Figure 7 Reliable rainfall stations in Gauteng.

2.3 Design rainfall depths

Although the focus of this study is on design storm shapes, design rainfall depths also play a crucial role in design storm generation. A previous study by Smithers and Schulze (2003) used rainfall data up to the year 2000 to determine regionalized design rainfall depths for South Africa. Since the data used for the Smithers and Schulze study was more than 20 years old when this project commenced, it was necessary to compare the results from that study with the design rainfall depths for this study.

To determine the at-site short duration design rainfall depths for this study, the AMSs were extracted using the sixteen durations used by the Design Rainfall Estimation in South Africa (DRESA) software (Smithers and Schulze 2003). The sixteen durations include the 5, 10, 15, 30, and 45-min, as well as 1, 1.5, 2, 4, 6, 8, 10, 12, 16, 20, and 24-hours. These durations were renamed to standard time steps to avoid confusion with the storm duration of an observed rainstorm event.

The AMS for the standard time steps were extracted for hydrological years (i.e., 1 October and 30 September). The General Extreme Value (GEV) distribution with linear moments was found by Smithers and Schulze (2000) to be appropriate for design rainfall estimations in South Africa. Therefore, the GEV method was applied to the AMS for the standard time steps to determine at-site design rainfall values for this study.

The Average Relative Difference (ARD) between the at-site design rainfall and the regional approach design rainfall obtained from DRESA, was determined. This comparison was used as a

final check to identify inconsistencies in the at-site design rainfall. The ARD for the 1:5, 1:10, and 1:20 years Recurrence Interval (RI) of time step t was determined using Equation 4.

$$ARD = \frac{1}{N_T} \cdot \sum_{i=1}^{N_T} \frac{P_{ASi,j} - P_{RAi,j}}{P_{RAi,j}} \cdot 100 \quad (4)$$

Where:

ARD = average relative difference for time step t ,

N_T = number of RIs (3),

$P_{ASi,j}$ = at-site design rainfall for time step i and $RI = j$ (mm), and

$P_{RAi,j}$ = design rainfall estimated using the regional approach from DRESA for time step i , and $RI = j$ (mm).

2.4 Storm coefficient for CDS Method

The storm advancement coefficient, associated with the Chicago Design Storm (CDS) method, was determined using Keifer and Chu's (1957) approach. Their approach is comprised of:

1. Identifying the maximum rainfall within a 15, 30, 60, and 120-min period within each significant storm event;
2. Identifying the ordinal position of the 5-min interval with the maximum rainfall for each period;
3. Determining the location of the peak intensity for each period;
4. Determining the weighted average for each significant event by using the location of peak intensity and weighted proportionally to 15, 30, 60, and 120-min; and
5. Determining the average for all significant events. This approach is summarised in Equation 5.

$$r = \frac{1}{N_s} \sum_{s=1}^{N_s} \frac{\sum_{j=1}^{N_d} t_i \cdot (n_{j,s} - 0.5)}{\sum_{j=1}^{N_d} d_{j,s}} \quad (5)$$

Where:

$d_{j,s}$ = durations ($j_1 = 15$ -min, $j_2 = 30$ -min, $j_3 = 60$ -min, $j_4 = 120$ -min) for rainstorm events,

N_d = number of specific storm durations (4),

N_s = number of significant storm events of station s ,

$n_{j,s}$ = ordinal position of 5-min interval with highest rainfall, and

t_i = duration of interval (5) (min).

Significant storm events were identified for the five best stations using a maximum dry period between rainfall spells of 15-min, minimum rainfall of 10 mm per event, and the minimum rainfall intensity of 1:2-year RI for all standard time steps (Mouton et al. 2022). The first criterion was applied to separate the data sets into 2 x 156 independent events. The second and

third criteria were applied to eliminate 1 x 838 insignificant events (<1:2 year). The remaining 318 events were considered significant ($\geq 1:2$ year) and were used for subsequent analyses. The significant rainstorm events were used to determine the storm advancement coefficient using Equation 5.

To determine IDF regression coefficients for the CDS method, a procedure was developed using the Generalised Reduced Gradient (GRG) nonlinear optimisation algorithm, developed by Lasdon et al. (1978). The algorithm adjusted the coefficients until the simulated intensities, using the Sherman (1931) formula (Equation 1), were approximately equal to the actual intensities from the design rainfall obtained from the DRESA software, divided by their respective durations.

The Goodness-of-Fit (GOF) between simulated and actual intensities was determined using the Root Mean Square Error (RMSE), presented as Equation 6.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N_t} (I_{a_i} - I_{s_i})^2}{N_t}} \quad (6)$$

Where:

$RMSE$ = root mean square error,

I_{a_i} = actual design rainfall intensity for time step i (mm/hour),

I_{s_i} = simulated design rainfall intensity for duration i (mm/hour), and

N_t = number of time steps (16).

The built-in solver function in Microsoft Excel, using the GRG nonlinear algorithm as the solving method and the calculated RMSE value as the objective value, was used for this procedure. However, because the GRG algorithm finds a local optimum solution, the results were, therefore, dependent on accurate starting values for the coefficients. Starting values of 1 000, 10, and 1, for the a , b , and c coefficients, respectively, were found to be efficient.

2.5 Storm shape assessment

The synthetic design storms that were generated with the CDS, SCS-SA, and the REC methods were compared with the 318 observed significant rainstorm events in terms of their shape and intensity. Based on the location of Gauteng and the previous regionalization by Weddepohl (1988) (Figure 3), the SCS-SA Type 2 and Type 3 curves were assessed. The GOF for both the shape of the mass curves, and the average intensities were assessed using the Mean Absolute Relative Error (MARE) method expressed in terms of Equation 7.

$$MARE = \frac{1}{N_d} \sum_{i=1}^{N_d} \left[\frac{|S_{ij} - O_{ij}|}{O_{ij}} \right] \quad (7)$$

Where:

$MARE$ = mean absolute relative error,

S_{ij} = synthetic intensity for storm j (mm or mm/hour),

O_{ij} = observed intensity for storm j (mm or mm/hour), and

N_d = number of 5-min data points or number of durations.

The effect of the peak intensity's position on the GOF was investigated by reducing the advancement coefficient. The SCS-SA curves were recreated using the GRG nonlinear optimisation algorithm described in Section 2.4 to determine their IDF regression coefficients used in the CDS method.

2.6 Design rainfall ratios for SCS-SA curves

The at-site design rainfall ratios (D-hour to 24-hour) were calculated and then compared with the ratios associated with the SCS-SA curves. The maximum ratio for a particular standard time step range and RI was determined for all stations, respectively, and called Intermediate Curve (IC) values. Municipal stormwater infrastructure associated with minor stormwater drainage networks is generally designed to accommodate storm events with an RI of 1:5 up to 1:20 years. The typical time of concentration of small urban catchments targeted in this study is assumed to be equal or less than 30-min. Therefore, the 5 to 30-min range and 1:5 to 1:20 year RIs were used for this study.

The regionalization of the at-site IC values was achieved by geographical interpolation using the Inverse Distance Weighting (IDW) method at a spatial resolution of 15 arc second intervals. The IDW exponent has a significant effect on the resulting surface. According to Shepard (1968), an exponent value higher than two results in even interpolated surfaces, whereas a value lower than two resulted in flat surfaces with rapid changes in the interpolated values near known points. Moeletsi et al. (2016) evaluated the IDW method for patching daily rainfall over the Free State Province, South Africa. This province borders Gauteng to the south. They assessed exponents at 0.5 intervals, starting from one to five. They found the exponents 2.0 and 2.5 both accurately predict rainfall at the targeted stations as compared to their measured rainfall. Therefore, an exponent of 2.5 was used to produce regionalized IC values for Gauteng.

3. RESULTS

3.1 Design rainfall depths

The at-site design rainfall for the sixteen reliable stations in Gauteng was determined and compared with the DRESA design rainfall of Smithers and Schulze (2003). The ARD was calculated using Equation 4. The average relative differences between the at-site values and DRESA for the three studied return periods, for all stations, are depicted in Figure 8. The results are presented in the form of a box plot with individual results for selected stations also shown. The selected stations consist of the five best stations (OR Tambo, Irene, Vereeniging, Jhb Bot Gardens, and Unisa), as well as the two stations with inconsistent results (Proefplaas and Alexandra). Durations of up to 24 hours are shown, as all other durations were originally described as ratios of the 24-hour rainfall in Weddepohl (1988).

Outliers were defined as values exceeding 1.5 times the interquartile range, which is the difference between the first quartile and third quartile values (Schwertman et al. 2004). The Proefplaas and Alexandra stations were inconsistent with DRESA and were classified as outliers. On this basis, these two stations were eliminated from subsequent assessment.

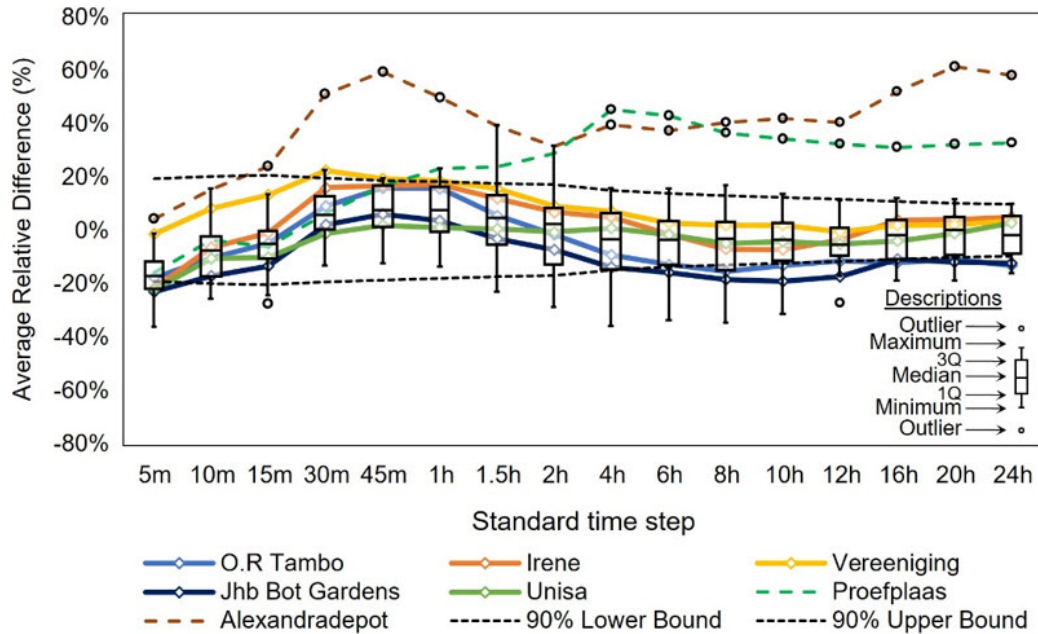


Figure 8 Average relative difference between at-site and DRESA (Smithers and Schulze 2003) design rainfall for 16 stations for the return periods used in this study.

The ARDs of the 5 to 15-min time steps were observed to be mostly negative, and the 30-min to 1.5-hour mostly positive. This means the design rainfall estimated by DRESA (Smithers and Schulze 2003) were less than the at-site design rainfall for the 5 to 15-min time steps, and for the 30-min to 1.5-hour time steps it exceeded the at-site design rainfall. The five best stations followed the same trend and were mostly between the first and third quartile values. Several at-site design rainfall exceeded the 90% upper and lower bounds given by the DRESA software (Smithers and Schulze 2003), considering the minimum and maximum values of the box plot. The highest differences were observed at the minimum values for the 1.5 to 24-hour and the maximum values for the 1.5 and 2-hour time steps, but the first and third quartile's ARDs were mostly within the bounds. Therefore, the estimation of the DRESA (Smithers and Schulze 2003) design rainfall was deemed acceptable in the selected pilot study area, even though it was developed using data up to the year 2000.

3.2 Application of the CDS Method

The DRESA design rainfall (Smithers and Schulze 2003) was used to determine the IDF regression coefficients, using Equation 1 and the GRG nonlinear optimisation algorithm. The relative errors of the simulated intensities were less than 5% when compared with the DRESA design rainfall intensities. This procedure was accepted to produce accurate IDF regression coefficients using the DRESA design rainfall. The regression coefficients for the 14 reliable stations used in this study are provided in Table 1.

Table 1 CDS regression coefficients determined from the DRESA design rainfall.

Name	a			b	c
	1:5	1:10	1:20		
Jhb OR Tambo	732	885	1047	4.269	0.726
Irene	745	901	1067	4.528	0.735
Bolepi House	988	1195	1414	5.621	0.756
Vereeniging	781	913	1040	5.086	0.752
Jhb Bot Gardens	723	874	1035	4.101	0.720
Bronkhorstspuit	991	1198	1418	5.693	0.757
Pretoria Unisa	992	1200	1420	5.710	0.757
Westonaria Kloof	738	862	982	4.339	0.729
Goudkoppies	741	895	1059	4.423	0.730
Dube	741	896	1060	4.430	0.731
Sterkfontein	715	850	988	3.926	0.715
Diepsloot	968	1170	1386	5.954	0.766
Shosanguve	988	1195	1414	5.686	0.757
Wonderboom	990	1196	1416	5.768	0.759

The storm advancement coefficient was calculated from the significant storm events identified from the five stations with the best data sets in Gauteng, namely, O.R Tambo, Irene, Vereeniging, Jhb Bot Gardens, and Unisa. As shown in Figure 9, the average advancement coefficient for Gauteng was calculated at 0.380. This result is similar to the coefficient of 0.376, proposed by Keifer and Chu (1957) for the City of Chicago.

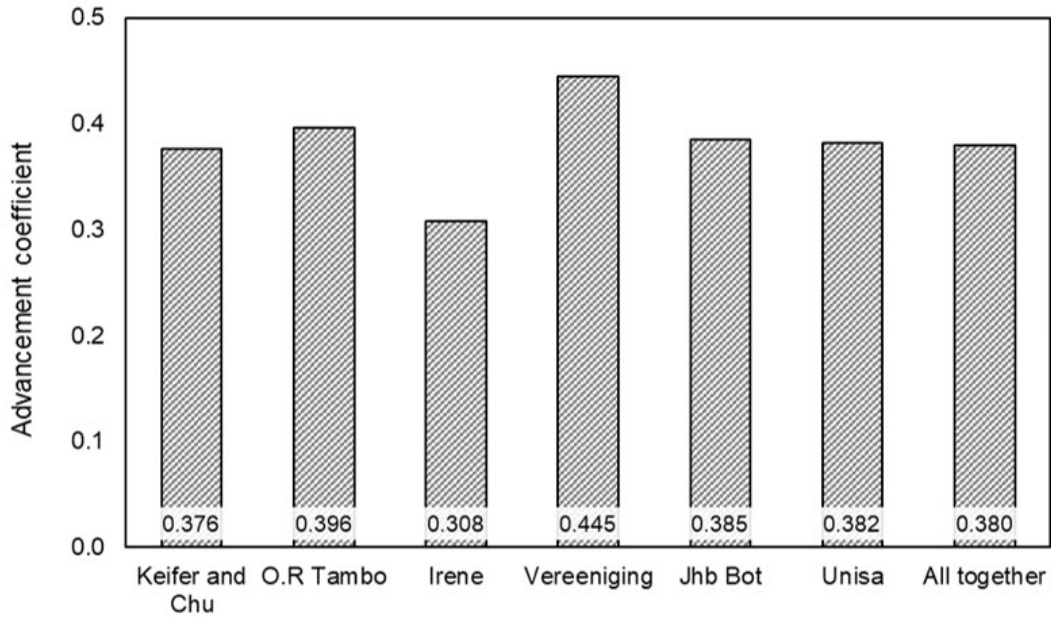


Figure 9 Average storm advancement coefficients, based on Keifer and Chu's (1957) second approach.

3.3 Performance assessment

The 318 identified significant storm events were also used for the mass curve assessment using Equation 7, with the results depicted in Figure 10. The results are presented in the form of a box plot. It was observed that the REC, with the lowest MARE value, best represented observed events in terms of mass curve shape when analysed in this manner.

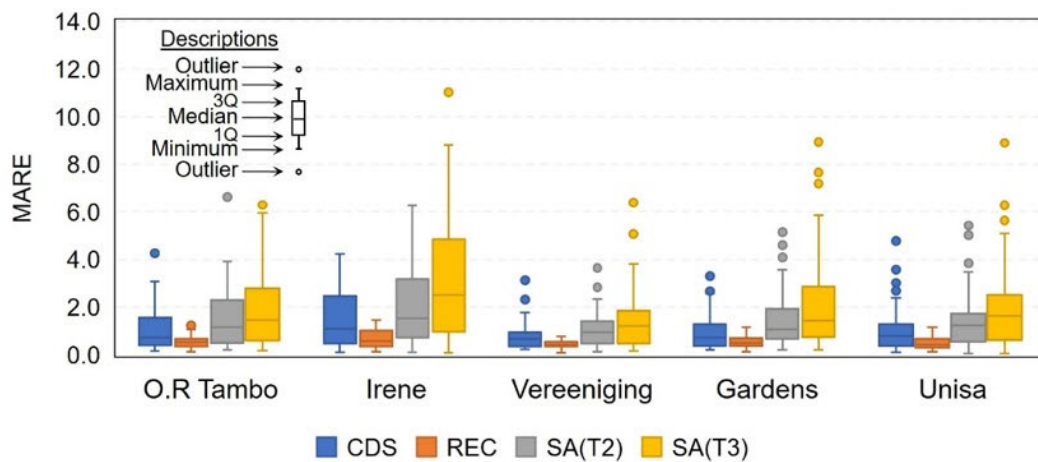


Figure 10 Mass curve shape assessment results.

The poor performance of the CDS and SCS-SA Types 2 and 3 was because of the position of the peak intensity relative to the total duration. The peak intensity for SCS-SA is in the middle of the event, whereas with CDS it is slightly earlier. The effect of the peak intensity's position was investigated by reducing the advancement coefficient. The SCS-SA curves were recreated using the GRG nonlinear optimisation algorithm to determine the IDF regression coefficients used in the CDS method.

Moving the peak intensity earlier resulted in significantly improved MARE values for the CDS and SCS-SA. The advancement coefficient was altered until a value of 0.01 was found to produce the best results, as depicted in Figure 11. An insert of the results is provided at a reduced scale. This advancement coefficient is significantly lower than the coefficient found using the method proposed by Keifer and Chu (1957). The difference between CDS and SCS-SA using the reduced advancement coefficient was insignificant, but with their peak intensities earlier during the storm event, they were a better representation of natural storm events than the REC. The number of outliers has also reduced compared to the results of their original shape.

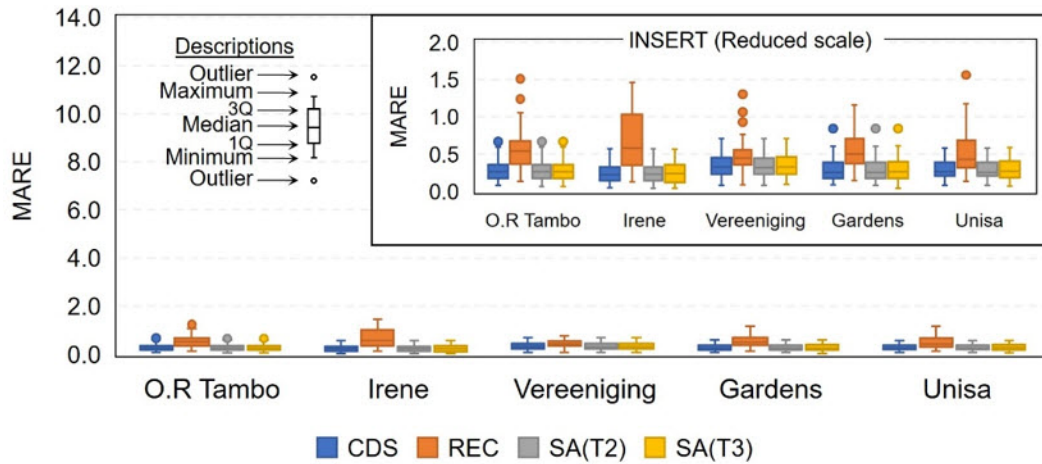


Figure 11 Modified shape assessment results.

The results for the average intensity assessments are depicted in Figure 12, with an insert of the results at a reduced scale. This indicates the REC, with its uniform intensity distribution, to be the worst representation of the observed rainstorm events. The CDS and SCS-SA were more representative with their varying intensity distribution. Several outliers were identified, which could be because of the assumed constant RI of these methods.

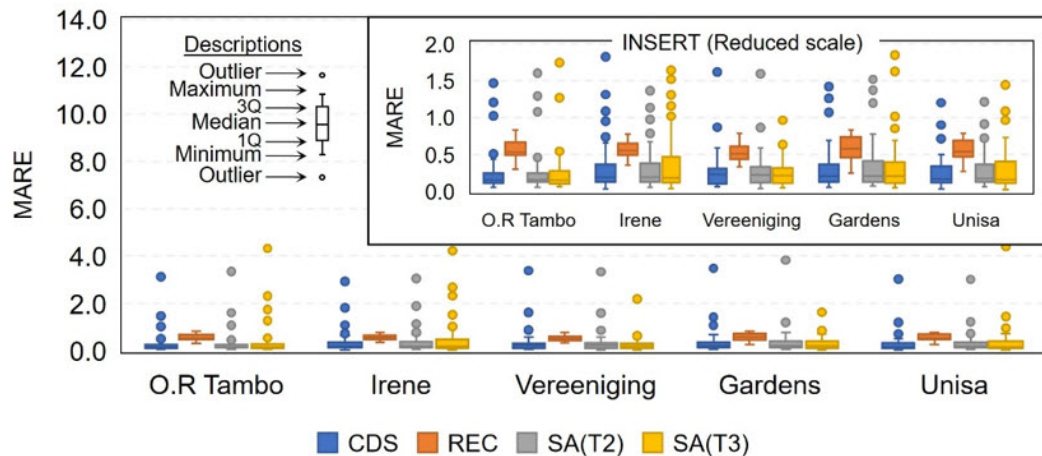


Figure 12 Average intensity assessment results.

3.4 Assessment of SCS-SA rainfall distribution curves

The at-site design rainfall of the fourteen stations with consistent results was used to calculate the D-hour to 24-hour design rainfall ratios. The ratios were compared with the equivalent SCS-SA ratios. The results for O.R. Tambo are depicted in Figure 13(a) as an example of the ratios, with the ratios of all four SCS-SA curves shown. It is evident that the at-site ratios are approximately equal to Type 2, rather than Type 3, as previously regionalized by Weddepohl (1988). However, simply using Type 2 may lead to underestimation of peak design intensities. Therefore, a novel approach was developed, where the position of the at-site ratios relative to the ratios of the four SCS-SA curves were linearly interpolated. The resulting values were called Intermediate Curve (IC) values, as depicted in Figure 13(b). The values (1 to 4) on the vertical axis represent the four standard type curves, rather than their ratios.

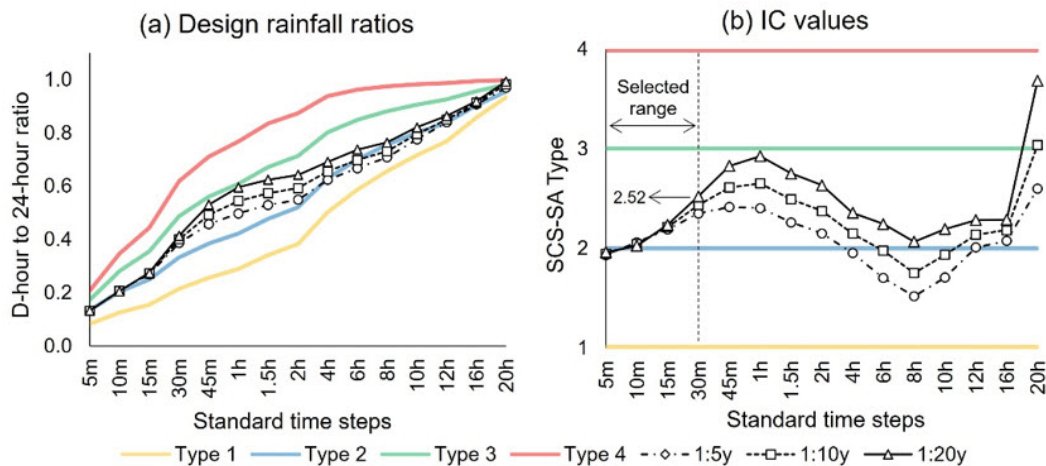


Figure 13 D-24-hour ratio and IC values for O.R. Tambo.

The IC values for the 1:5 to 1:20 year, 5-min time step, for example, are similar at 1.95 (approximately equal to Type 2) but increased to between 2.40 and 2.93 (between Type 2 and Type 3) at the 1-hour time step. The same variation in IC values was observed at all stations. However, the time of concentration of an urban catchment size targeted in this study was assumed to be less than 30-min. Therefore, the maximum IC value of the 5 to 30-min duration range, for the 1:5 to 1:20 year RIs at O.R. Tambo, was determined to be 2.52, as shown in Figure 13(b). The maximum IC values at all fourteen stations were determined in the same way and then regionalized.

The Inverse Distance Weighting (IDW) method was applied to produce a map with regionalized IC values for Gauteng, as depicted in Figure 14. A comparison of Figure 14 with Figure 5 and Figure 6 shows that neither the elevation, nor LULC, has a significant correlation with the IC values in Gauteng. The averaged AMS for short duration rainfall (Figure 15) does show inverse proportionality to the IC curve for the north-east of the province, but no consistent trend is evident for the rest of the province. It can therefore be concluded that the elevation, landcover, and AMS cannot be used to reliably deduce IC values for Gauteng. The map in Figure 14 is proposed for determining the IC value at any ungauged site in Gauteng.

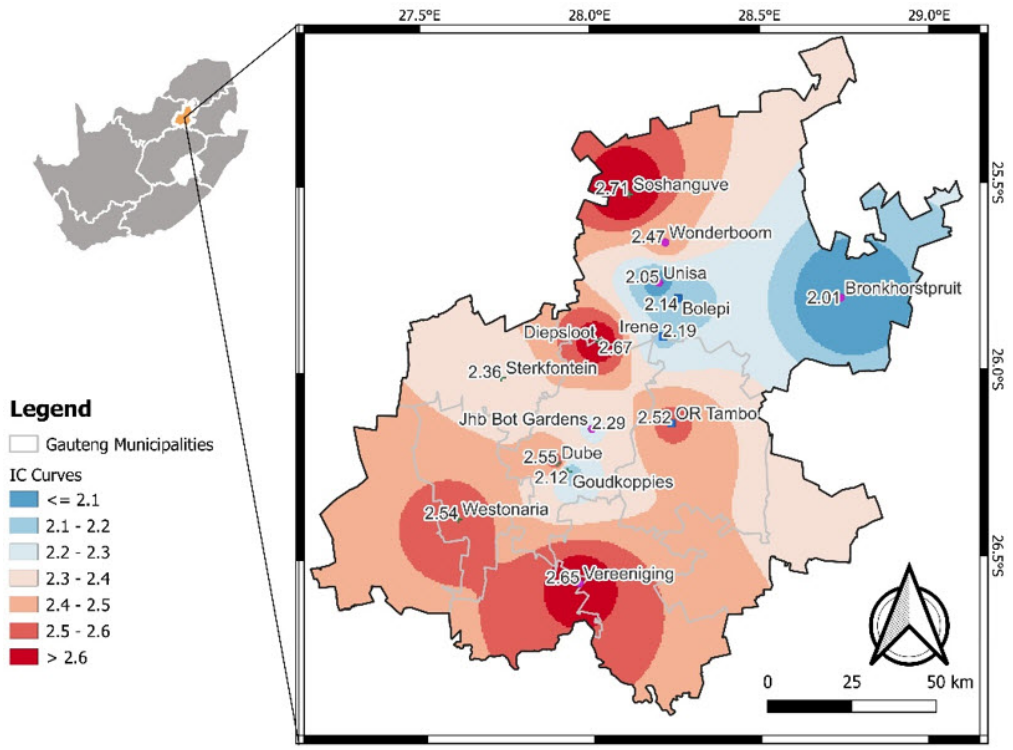


Figure 14 Regionalized IC values for Gauteng.

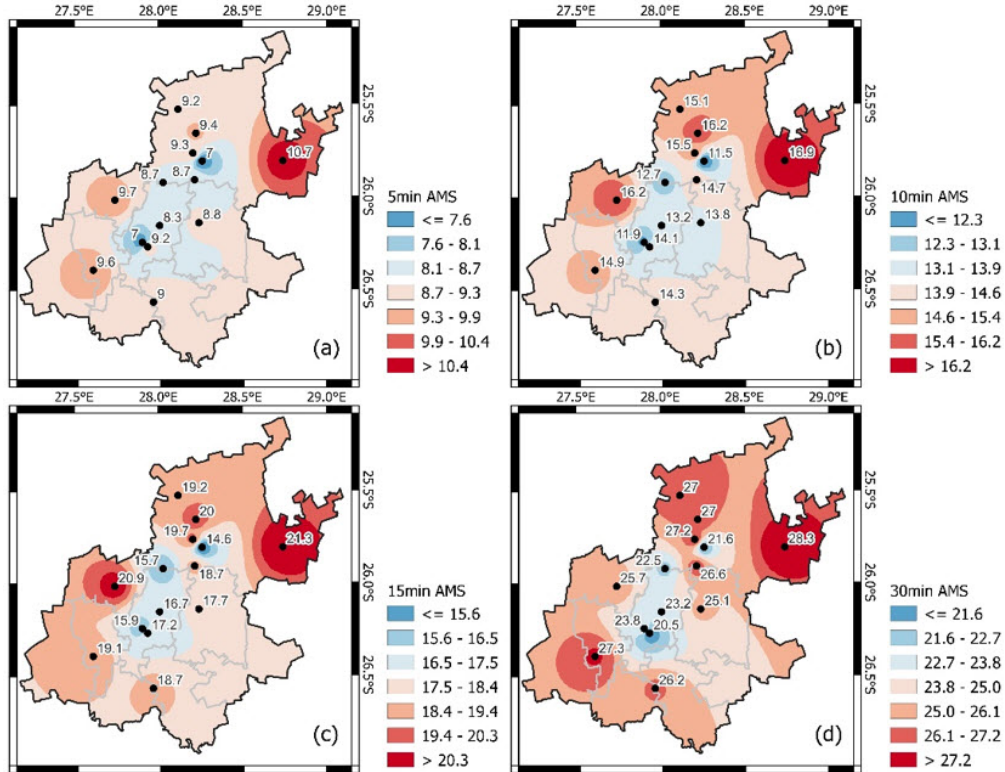


Figure 15 Spatial distribution of average AMS values for short-duration rainfall in Gauteng for (a) 5-min, (b) 10-min, (c) 15-min, and (d) 30-min durations.

The variation in IC values with duration is large, as shown in Figure 13, and between sites in Gauteng, as shown on Figure 14. Selecting an inappropriate curve will result in unrealistic peak discharge estimates when used as input for a single-event-based simulation. As a result, a linearly interpolated curve between the SCS-SA curves is proposed to generate synthetic design storms more accurately using Equation 8.

$$ICT_t = (IC - C_i) \cdot (RC_{i+1,t} - RC_{i,t}) + RC_{i,t} \quad (8)$$

Where:

- ICT_t = intermediate cumulative rainfall ratio for time step t ,
- IC = Intermediate curve value,
- C_i = SCS-SA curve i (IC value rounded down to the nearest integer),
- $C_{(i+1)}$ = SCS-SA curve type plus 1 (1, 2, 3, or 4), and
- $RC_{i+1,t}$ = cumulative rainfall ratio of SCS-SA curve $i+1$ for time step t .

4. CONCLUSIONS AND RECOMMENDATIONS

Three methods were used to develop synthetic design storms for small urban catchments in Gauteng, South Africa, of which two were identified to be appropriate. The CDS and SCS-SA methods have the ability to generate site-specific synthetic design storms by applying the proposed improvements in terms of:

- the representative advancement coefficient for Gauteng,
- estimating the IDF regression coefficients from the DRESA design rainfall using the GRG nonlinear optimization algorithm, and
- generating an intermediate curve, based on the regionalized IC values.

Their performances were evaluated based on the shape and the intensity distribution compared with observed rainstorm events. From the results presented, it was concluded that synthetic design storms generated with CDS and SCS-SA are more representative of observed storm events than storms generated with the REC method, provided that the position of the peak intensity was moved to the start of the storm. The performance of the CDS and SCS-SA also exceeded the REC in terms of intensity distribution.

The relationship between the hyetograph and hydrograph is affected by the catchment characteristics. Therefore, further research concerning the parameterization of synthetic design storms to improve the accuracy of single-event-based simulation modeling is recommended. The peak discharge and runoff volume can assist by comparing the results from event-based simulations with the results from continuous simulation applications of the model. Synthetic design storms with a storm duration of 2 hours will generally be adequate to exceed the longest time of concentration (Watson 1981), whilst longer durations will lead to higher levels of soil moisture content. The advancement coefficient of 0.380 was determined for Gauteng using Keifer and Chu's (1957) methodology, but a reduced coefficient of 0.010 was more representative of observed rainstorm events. The effect of the storm duration and storm advancement coefficient considering various catchment characteristics, should be investigated.

Antecedent moisture conditions in the study area should be quantified, as it is widely reported that this will significantly contribute to runoff peak and volume, and if the peak intensity occurs at the start of the storm, the model will not simulate saturated conditions during the peak runoff (De Michele and Salvadori 2002; Cao et al. 2020; Brunner and Dougherty 2022). The runoff volume should also be considered. Because the peak discharge from a single event-based model increases proportionally as the RI increases, a methodology can be adopted to improve the consistency between the runoff volume and peak discharge of the continuous simulation models (Mouton 2023).

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