PAPER 16

RETHINKING SYNTHETIC DESIGN STORMS: EVALUATING CLIPPED SCS-SA AND BIMODAL RAINFALL EVENTS FOR SMALL URBAN CATCHMENTS IN ETHEKWINI

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ABSTRACT

Rapid urbanisation and recent catastrophic flood events in eThekwini, South Africa, have intensified demands on existing stormwater infrastructure. Current local municipal guidelines rely heavily on assumed minimum times of concentration, which subsequently result in the widespread adoption of 20 to 30-minute synthetic design storm durations. Furthermore, these guidelines focus exclusively on single-peak synthetic design storms. This conventional approach ignores the hydrological reality of considerably longer-duration storms and the occurrence of complex, multi-peaked bimodal events, potentially leading to severely under-designed infrastructure. To address these critical gaps, this paper evaluates existing synthetic design storm methods and presents improved, regionally appropriate design storms for small urban catchments in eThekwini. Using 5-minute rainfall data sourced from 36 local rainfall stations with at least 10 years of reliable records, over 1000 major rainfall events (recurrence interval ≥ 2 years) were extracted and analysed using custom Python algorithms. The analysis reveals that bimodal storms comprise approximately 12% of all observed major storm events, representing a significant and previously overlooked component of the region's rainfall record. Crucially, the observed median durations for these major events are 130 minutes, and 298 minutes for the subset of bimodal storms, starkly contrasting with the 20 to 30-minute durations commonly assumed in municipal design.

The paper systematically evaluates the performance of standard single-peak methods, including Rectangular, Triangular, and an adjusted version of the standard 24-hour SCS-SA Type 1, 2, 3 and 4 design storms that were clipped to the observed storm durations. Performance is measured against observed single-peak events using Mean Absolute Relative Error (MARE), Peak Factor, and Volume Factor metrics. For bimodal events, two novel bimodal methodologies, *Bimodal-Same RI* and *Bimodal-Split R*, are developed and evaluated against the observed bimodal storm records.

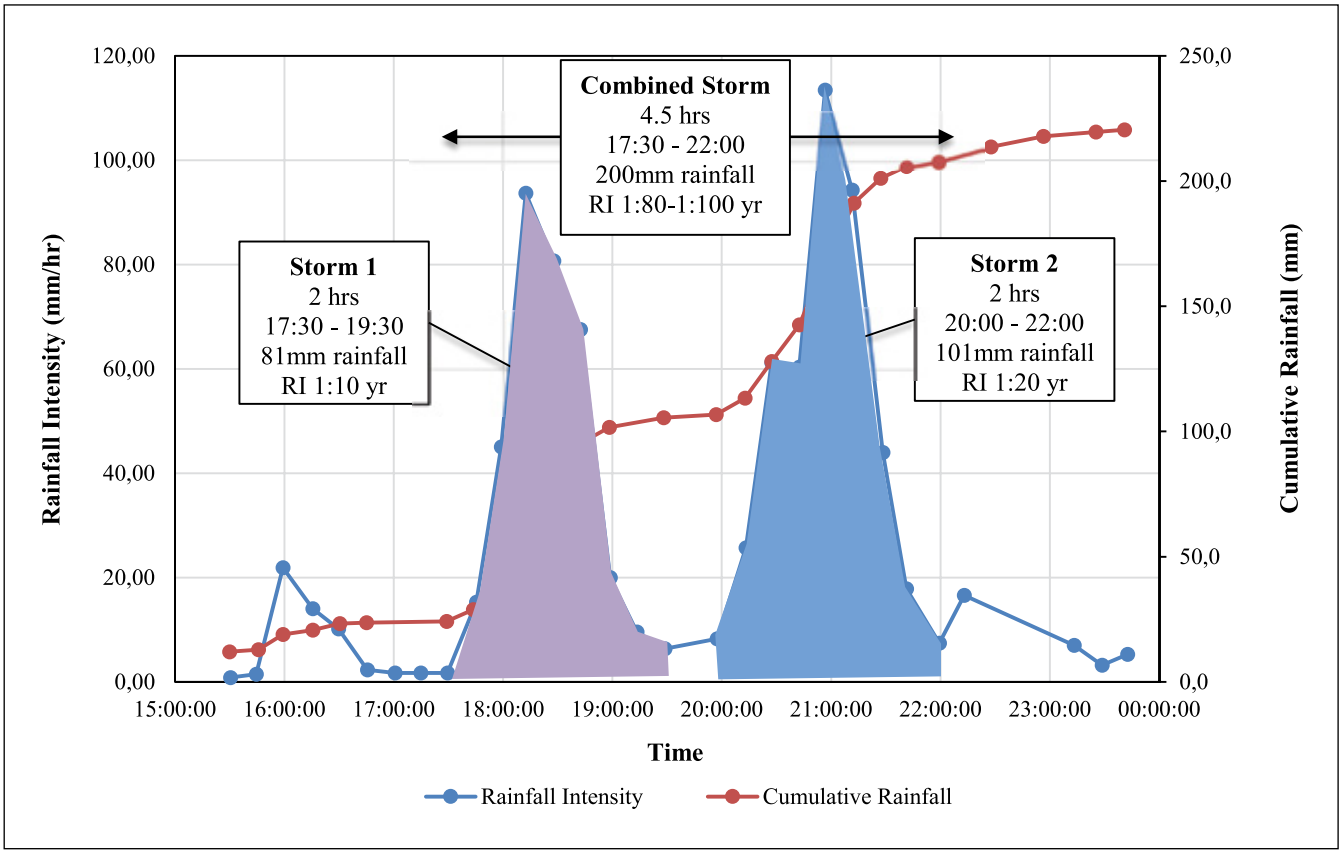


FIGURE 1: *Graphical representation of 13 April 2003 bimodal storm event in eThekwini (Morris 2003)*

The findings unequivocally demonstrate the superior performance of the clipped SCS-SA method (specifically SCS-SA Type 1) in accurately representing observed single-peak storm events. For bimodal events, the *Bimodal-Split R* method successfully captures the bimodal shape and volume without the severe overestimation observed with other methods. Ultimately, the paper provides actionable engineering recommendations for South African stormwater practice, advocating for a fundamental shift away from arbitrary assumed durations toward evidence-based median durations, and the formal adoption of both the clipped SCS-SA Type 1 and Bimodal Split R design storms to ensure future infrastructure resilience.

INTRODUCTION

eThekwini has experienced devastating flood events in recent years, including severe events in 2017, 2019, and 2022, which caused catastrophic economic and social losses. Estimated economic losses caused by these flood events escalated rapidly, from R576 million in 2017, to R1.8 billion in 2019, and exceeding R8 billion during the catastrophic April 2022 floods (eThekwini Municipality 2022). These events highlight an urgent need to review current stormwater design procedures to ensure future infrastructure is robust and capable of managing intense rainfall. Current municipal practices in eThekwini rely heavily on the Rational Method for minor urban stormwater systems, explicitly stipulating a minimum time of concentration of 10 to 15 minutes for small, developed urban catchments (eThekwini Coastal Stormwater & Catchment Management Department 2018). Consequently, stormwater engineers typically constrain design storm durations to approximately 20 to 30 minutes in many small catchments, drastically underestimating actual storm behavior.

This standard municipal methodology exclusively assumes a single-peak storm event. However, observed extreme floods, such as the devastating 2003 Umbogintwini Industrial Complex flood, have been driven by complex, double-peaked bimodal storms (Morris 2003). During this event, two distinct 2-hour storms occurred in close succession, resulting in initial rainfall saturating the catchment and drastically amplifying the runoff volumes and flow rates generated from the second peak. The resulting flood damage was equivalent to a 1:70-year to 1:100-year runoff event, despite the individual peaks having substantially lower return periods, as shown in Figure 1 (Morris 2003, Ninham Shand Consulting Services 2006). Bimodal storms are rarely accounted for in typical synthetic design storm methods.

Therefore, this paper aims to evaluate existing synthetic design storms and develop improved methodologies by addressing five critical questions:

(a) How common are bimodal storms within the observed dataset?
(b) How do observed storm durations compare with those commonly assumed in design?
(c) Which design storm best represents observed single-peak storm behavior?
(d) How well do the developed bimodal design storms represent observed bimodal storm behaviour?
(e) What are the implications for stormwater and hydrological design practice in South Africa?

METHODOLOGY

Major event isolation

To establish a reliable observed dataset for urban drainage analysis in eThekwini, 5-minute rainfall records were sourced from the municipality's Coastal, Stormwater and Catchment Management (CSCM) division. Quality control was performed using strict objective criteria: only stations with a record length of at least 10 years, and less than 10% missing data during the critical wet months were selected, resulting in a filtered dataset of 36 active stations. Erroneous data, such as duplicate entries, prolonged identical high readings indicating rain sensor malfunctions, and isolated 5-minute rainfall depths exceeding the 200-year design rainfall, were identified and removed by comparing annual totals with Mean Annual Precipitation (MAP) values obtained from the Design Rainfall Estimation for South Africa (DRESA) software (Smithers & Schulze 2003), which incorporates MAP raster data from Lynch (2004).

While a previous pilot study in Gauteng by Mouton *et al.* (2022) utilized a Java program named *Rain-Pro* (Munro 2021) and Microsoft Excel for temporal disaggregation, these tools struggled with processing speed, bimodal event identification, and data volume when applied to the eThekwini dataset. To address these functional limitations, a novel Python program, *STORM ID*, was developed to automate much of the data processing. To segment continuous rainfall records into discrete, independent storm events, a Maximum Dry Period (MDP) threshold was applied, representing the dry period between rainfall spells (Restrepo-Posada & Eagleson 1982; Mouton *et al.* 2022). While historical MDP values range from 1 hour up to 6 hours (Huff 1967; Ramlall 2020), this study performed a local sensitivity analysis on MDPs of 15, 30, 60, and 120 minutes. An initial MDP of 15 minutes aligned with the typical response time of small catchments in eThekwini. However, increasing the MDP beyond 30 minutes resulted in a notable decrease in the correlation between total rainfall depth and storm duration, as well as the premature merging of independent storms. Consequently, an MDP of 30 minutes was selected to isolate independent events while successfully preserving the internal dry spells (saddle points) characteristic of bimodal storm profiles.

To isolate hydrologically significant major events, the extracted storms were filtered using three physical criteria:

(a) Minimum Rainfall Depth (MRD): A threshold of 10 mm was applied to exclude minor, transient rain spells, consistent with the methodology of Mouton *et al.* (2022) and Spooner *et al.* (2026).
(b) Storm Duration Constraints: Only events with durations between 15 minutes and 24 hours were retained, excluding highly transient storm spells (under 15 minutes) with only 1 or 2 data points which force the peak to occur at the start or end of the event, and enabling standard clipping of 24-hour SCS-SA design storms.
(c) Minimum Recurrence Interval (MRI): An MRI threshold of 2 years was adopted, consistent with Mouton *et al.* (2022), to exclude non-critical events. While the eThekwini (2018) Stormwater Design Guidelines consider a 3-year or higher return period for drainage infrastructure, a 2-year MRI was practically adopted because DRESA design rainfall values are only available starting at a 2-year recurrence interval (Smithers & Schulze 2003). Applying this MRI threshold successfully eliminated over 90% of insignificant extracted storm events.

To determine the recurrence interval (RI) for each isolated storm event, a moving-window extraction was used to identify maximum rainfall depths over standard durations (5 to 120 minutes), which were then compared against station-specific design rainfall values from DRESA (Smithers & Schulze 2003). Using this methodology, the *STORM ID* program isolated a final dataset of 1071 major rainfall events in eThekwini, which had a mean storm duration of 255 minutes (median duration of 130 minutes), and a mean RI of 10 years (median RI of 4 years).

Bimodal event isolation

Following the isolation of the major events, these major events were analysed to determine the portion of events that had a bimodal distribution. To achieve this, major storm events with a bimodal rainfall

distribution first needed to be identified. Limited previous research exists on methodologies for this purpose, with previous studies using visual inspection for bimodal storm identification (Paton et al. 2024), a subjective approach that introduces bias and limits reproducibility. Therefore, Spooner *et al.* (2026) developed a novel approach to systematically isolate storm events with a bimodal distribution, using a set of objective criteria. A summary of the *STORM ID-BIMODAL* program criteria used to isolate bimodal events is shown below, with an accompanying graphical representation shown in Figure 4.

(a) $P_2 \geq a * P_1$
(b) $S_1 \leq b * P_2$
(c) $P_3 < c * P_2$ or if $P_3 \geq c * P_2$ then $S_2 > d * P_3$
where: $a = 0.7$, $b = 0.3$, $c = 0.7$ and $d = 0.3$.

These specific mathematical criteria and variable thresholds ensured that true bimodal events were robustly isolated from both single-peak (unimodal) and complex multimodal storms.

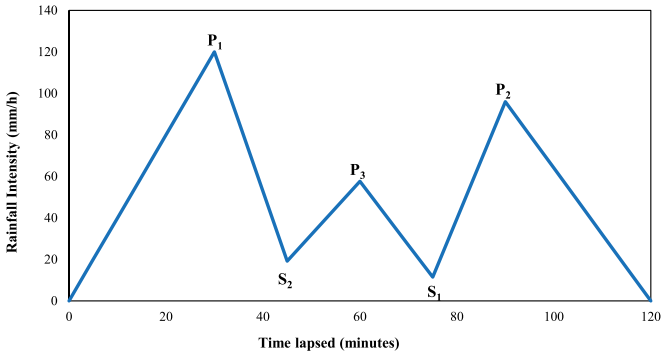


FIGURE 2: *Graphical representation of criteria used to isolate bimodal events.*

Design storm methods

This study evaluates specific single-peak design storms commonly used in hydrological practice, specifically: the Rectangular Design Storm (Mulvaney 1851), Triangular Design Storm (Yen & Chow 1980), and the standard SCS-SA Type 1, 2, 3, and 4 distributions (Schmidt & Schulze 1987). Because the standard SCS-SA curves were originally developed strictly for 24-hour durations, applying them directly to shorter events artificially compresses 24 hours of rainfall into a shorter window, causing severe intensity distortions. To resolve this, a Clipped SCS-SA method was applied. Using the technique proposed by Haan *et al.* (1994), this clipping method dynamically extracts the specific portion of the 24-hour distribution that contains the highest cumulative rainfall for the desired duration, effectively preserving the actual storm shape and relative intensity distribution without artificial compression. For example, keeping the 30 minutes before and after the peak to extract a 60-minute storm. Recalculating cumulative rainfall ratios within this isolated window discards the outer low-intensity tails. This approach successfully preserves the original storm shape and relative intensity distribution without artificial temporal compression and allowed the SCS-SA design storms to be compared to the observed storm events with varying durations.

To address bimodal events, Spooner *et al.* (2026) developed two novel bimodal triangular design storms, *Bimodal-Same RI* and *Bimodal-Split R*, drawing on the bimodal triangular profiles of Lambourne and Stephenson (1987) and Yen and Chow's (1980) triangular design storm. Both methods utilise constant, time-related shape parameters derived directly from regional observed data: a mean time-to-saddle ratio ($S_O = 0.46$) and mean dimensionless times-to-peak for the first ($A_1 = 0.68$) and second ($A_2 = 0.25$) embedded storms. These ratios divide the bimodal storm duration (T_D) into two distinct, successive triangular events (T_{D1} and T_{D2}) separated by an inter-peak saddle point (S_1). Figure 3 shows a graphical representation of the time-related shape parameters used in the development of the bimodal design storms.

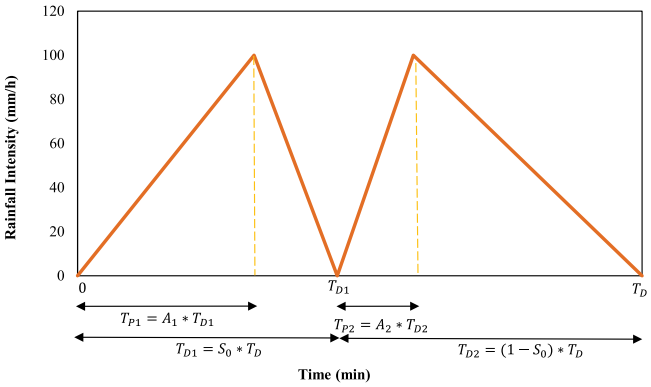


FIGURE 3: *Typical bimodal triangular hyetograph showing time-related shape parameters used in the development of the bimodal design storm.*

While sharing identical timing, the two bimodal methods differ fundamentally in how they calculate rainfall volume and peak intensity:

(a) *Bimodal-Same RI*: Assumes both embedded triangular storms share the exact recurrence interval of the total isolated bimodal event. As a result, their peak intensities differ. While this method successfully replicates the magnitude of separate storm peaks, assuming a matching extreme RI for both successive peaks often leads to substantial overestimations of total storm volume and runoff (Spooner *et al.* 2026).

(b) *Bimodal-Split R*: Proportionally splits the total rainfall volume of the entire bimodal event across the two embedded triangular storms based on their individual durations. This distribution forces equal peak intensities for both embedded storms, preventing severe volume overestimation (Spooner *et al.* 2026).

RESULTS

Prevalence and significance of bimodal storms

A total of 1071 major storm events were isolated across the 36 stations using the 30-minute MDP criterion. By systematically evaluating peaks, valleys, and saddle points using the custom *STORM ID-BIMODAL* Python tool, it was determined that 128 of these events exhibited a distinct bimodal distribution. Consequently, bimodal storms comprise approximately 12% of the observed major events dataset. This confirms that double-peaked events are not isolated anomalies but rather a frequent component of the local rainfall record in eThekwini.

Furthermore, bimodal events are substantially more severe than typical single-peak storms. The mean recurrence interval for bimodal events was calculated at 22 years, which is more than double the mean recurrence interval of 10 years calculated for all major events combined. Bimodal events are disproportionately represented at extreme return periods; notably, 5.5% of all bimodal events had an RI greater than 200 years, compared to just 0.7% for the full dataset. The distribution of recurrence intervals for bimodal events isolated in this study is shown in Figure 4.

Observed vs. Assumed storm durations

Current eThekwini guidelines enforce assumed minimum design storm durations of 20 to 30 minutes for small urban catchments, derived directly from simplified minimum time of concentration rules (eThekwini Coastal Stormwater & Catchment Management Department 2018). However, as demonstrated by the dataset, the observed median storm duration for all major events isolated in this study is 130 minutes, while the mean duration stretches to 255 minutes. The highest frequency of major events recorded had durations ranging from 30 to 90 minutes, completely eclipsing the 20-minute design assumptions.

The discrepancy is even more severe for complex, multi-peaked systems. Bimodal events exhibited an observed median duration of 298 minutes and a mean of 405 minutes, with the 75th percentile of bimodal storms lasting over 10 hours, as shown in Figure 5. These findings confirm that relying strictly on a catchment's minimum time of concentration significantly underestimates the true length and total volumetric load of local rainfall events. In practice, underestimating the total volumetric load can lead directly to the underdesign of stormwater attenuation facilities and piped reticulation networks, leaving critical urban infrastructure vulnerable to capacity exceedance and severe localised flooding.

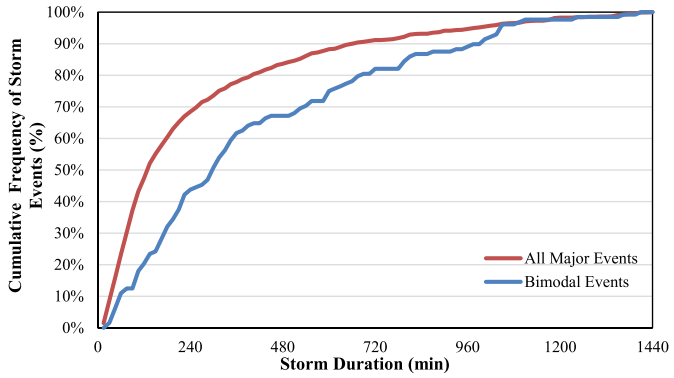


FIGURE 5: *Cumulative frequency distribution of all major and bimodal events' storm durations*

Performance of single-peak design storms

The performance of the single-peak design storm methods was systematically evaluated against the 1072 isolated major rainfall events. For each observed event, corresponding design storms were generated using the same storm duration and RI and subsequently compared with the observed events. Three evaluation metrics were employed: the Mean Absolute Relative Error (MARE), which quantified differences in rainfall intensity distribution across all time steps; the Peak Factor (PF), which

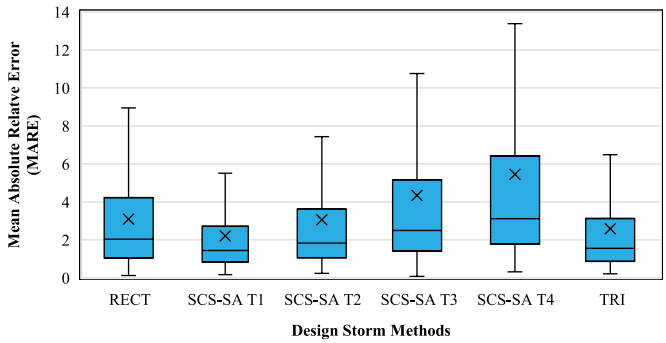


FIGURE 6: *Box-whisker plot of MARE values for each single-peak design storm method*

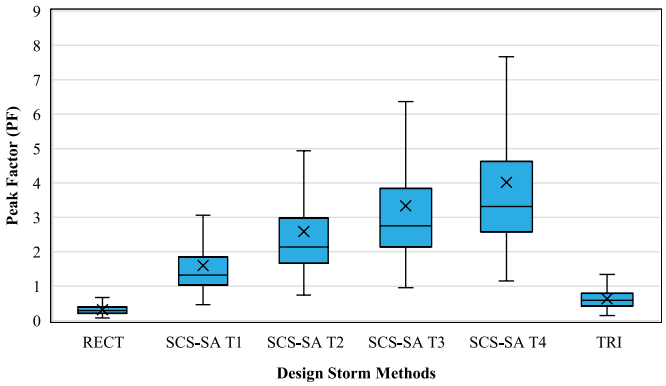


FIGURE 7: *Box-whisker plot of PF values for each single-peak design storm method*

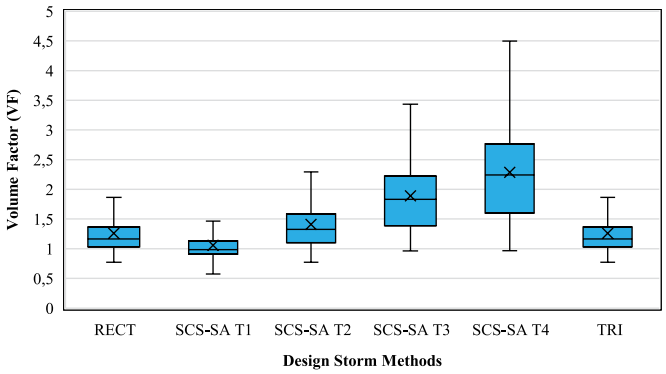


FIGURE 8: *Box-whisker plot of VF values for each single-peak design storm method*

compared the maximum rainfall intensity of each design storm with the observed peak intensity; and the Volume Factor (VF), which compared the total cumulative rainfall depth of each design storm with that of the observed event. The distributions of these performance metrics for all design storm methods are presented as box and whisker plots in Figure 6, Figure 7 and Figure 8, illustrating the mean (), median, interquartile range, and minimum and maximum values.

The SCS-SA Type 1 design storm (SCS-SA T1), when clipped to storm duration using the Haan *et al.* (1994) extraction technique, demonstrated superior performance across all of the evaluation metrics used. It yielded the lowest overall temporal error with a mean MARE of 2.21, indicating it was the most consistent single-peak method for replicating the temporal distribution of observed rainfall intensities in eThekwini.

In terms of peak intensity, SCS-SA T1 produced a mean Peak Factor (PF) of 1.60 and a median PF of 1.32. While both the RECT (mean PF of 0.26) and TRI (mean PF of 0.63) methods consistently and significantly underestimated peak intensities, SCS-SA T1 provided a conservative, design-appropriate overestimation of the peak. Furthermore, SCS-SA T1 proved to be the most accurate method for estimating total rainfall volumes, achieving a mean Volume Factor (VF) of 1.06 and a median VF of 0.99. This means it almost perfectly replicated actual storm volumes without inducing the severe volumetric overestimations characteristic of the regional SCS-SA Type 2 (mean VF of 1.40), Type 3, and Type 4 distributions.

Performance of bimodal design storms

To assess their practical viability for engineering applications, the developed bimodal synthetic design storms were evaluated against the

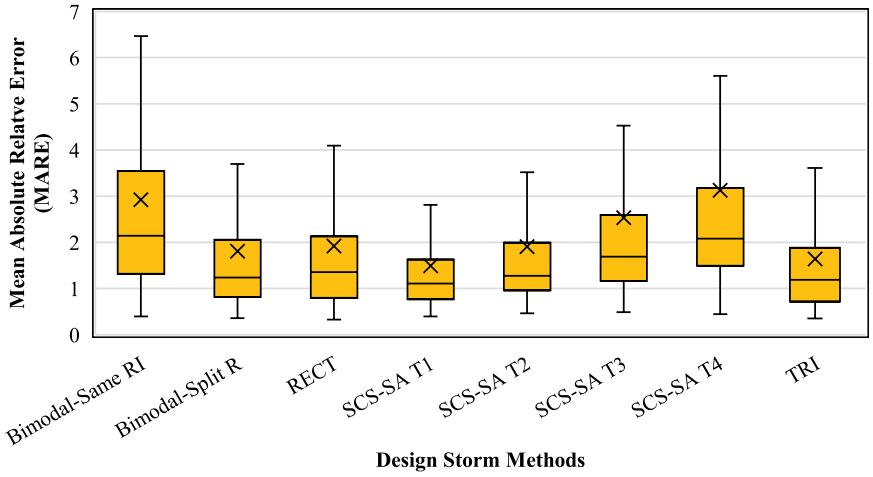


FIGURE 9: *Box-whisker plot of MARE values for each bimodal and single-peak design storm method across each bimodal event*

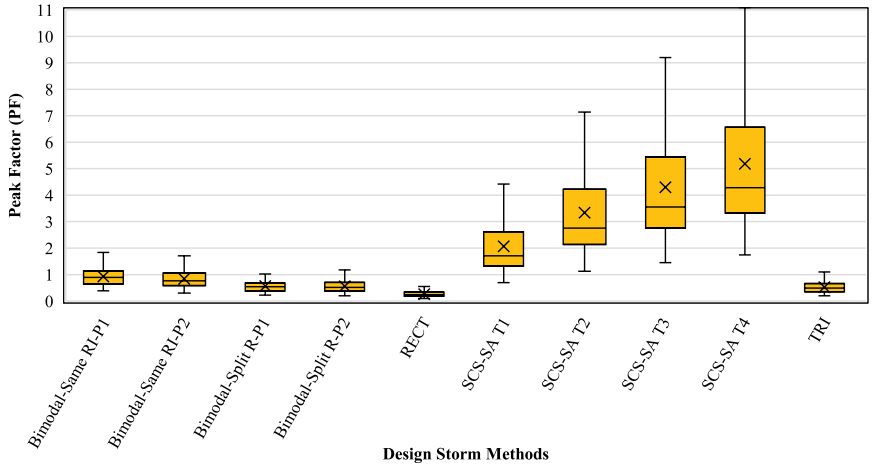


FIGURE 10: *Box-whisker plot of PF values for each bimodal and single-peak design storm method across each bimodal event*

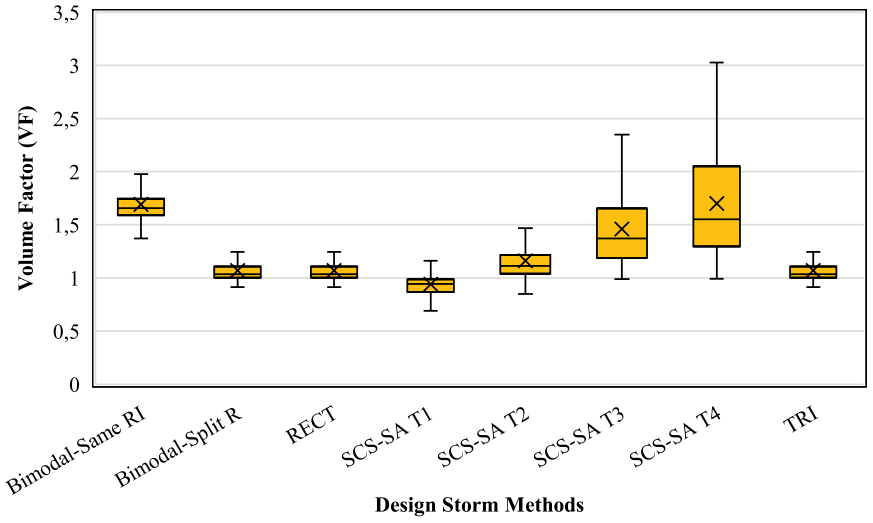


FIGURE 11: *Box-whisker plot of VF values for each bimodal and single-peak design storm method across each bimodal event*

128 isolated observed bimodal rainfall events. Performance was assessed using the same evaluation metrics employed for the single peak design storm methods, with the Mean Absolute Relative Error (MARE), Peak Factor (PF), and Volume Factor (VF) calculated for each event. In addition, the *Bimodal-Same RI* and *Bimodal-Split R* design storm methods were compared directly with the conventional single peak design storm methods to evaluate whether they provided a more accurate representation of the observed bimodal rainfall events. The distributions of these performance metrics for all design storm methods are presented in Figure 9, Figure 10 and Figure 11 as box and whisker plots in, illustrating the mean (), median, interquartile range, and minimum and maximum values.

The *Bimodal-Same RI* method most accurately replicated the magnitudes of the two embedded rainfall peaks, achieving mean Peak Factors (PF) of 0.93 and 0.89 for the primary and secondary peaks, respectively. By applying the event recurrence interval independently to both embedded storms, the method successfully captured the peak intensities of double peak systems. However, this independent scaling substantially overestimated the total storm volume, producing a mean Volume Factor (VF) of 1.70 and the second highest MARE of all methods evaluated (2.92).

Conversely, the *Bimodal-Split R* method prioritised volumetric accuracy by proportionally distributing the total design rainfall volume between the two embedded storms according to their relative durations. This approach achieved a highly accurate mean VF of 1.07 (median = 1.04) while substantially improving overall shape representation, returning a mean MARE of 1.81. Although enforcing equal peak intensities resulted in an underestimation of individual peak magnitudes (mean PF = 0.56), the method successfully preserved the total event volume.

Compared with conventional single peak design storms, the bimodal methods demonstrated clear structural advantages for representing double peak rainfall events. In particular, the *Bimodal-Split R* method provided the most balanced representation by accurately reproducing total rainfall volume and storm timing while explicitly accounting for the double peak structure that cannot be represented by conventional single-peak design storms.

CONCLUSIONS

Based on the comprehensive evaluation of 1072 major rainfall events in the eThekwini region, this study demonstrates that bimodal rainfall events are a frequent and hydrologically significant component of the local climate, accounting for approximately 12% of all major storm events. These events are not isolated anomalies but represent highly severe, long duration storm systems, with a mean recurrence interval of 22 years, more than double the 10-year mean recurrence interval of the complete dataset. The analysis

further revealed that observed storm durations substantially exceed those assumed in current municipal design practice. Median durations of 130 minutes for single-peak events and 298 minutes for bimodal events are considerably greater than the 20-to-30-minute design storm durations currently recommended in local guidelines. Consequently, the continued use of minimum times of concentration to define storm duration is likely to underestimate storm persistence, runoff volumes, and the capacity requirements of stormwater infrastructure.

Among the conventional single-peak design storm methods, the clipped SCS-SA Type 1 design storm, developed by shortening the standard SCS-SA Type 1 distribution to observed storm durations using the Haan *et al.* (1994) clipping technique, provided the most representative simulation of observed rainfall events. This method consistently outperformed the alternative distributions by closely reproducing both the temporal rainfall distribution and total storm volume, achieving a mean Volume Factor of 1.06. For bimodal rainfall events, the newly developed *Bimodal-Split R* design storm provided the most balanced representation. Using constant time-related shape parameters, together with a proportional allocation of total rainfall volume between the two embedded storms, the method accurately reproduced the temporal structure and total rainfall volume of observed bimodal events while achieving a mean Volume Factor of 1.07. In contrast, the *Bimodal-Same RI* method, although accurately reproducing peak rainfall intensities, overestimated total storm volumes by approximately 70% because the event recurrence interval was applied independently to both embedded storms.

Overall, the findings indicate that current stormwater design practice in eThekwini underestimates both storm duration and the complexity of local rainfall by relying on short duration, single-peak design storms. Incorporating evidence-based storm durations together with the clipped SCS-SA Type 1 design storm for single-peak events and the *Bimodal-Split R* design storm for bimodal events would provide a more representative basis for hydrological design, improving estimates of runoff volume and enhancing the resilience of urban stormwater infrastructure to major flood events.

RECOMMENDATIONS

To ensure that future stormwater infrastructure is robust, resilient, and scientifically grounded, the following updates are recommended for local municipal engineering practice:

(a) Update storm durations used: Practitioners must formally move away from fixed 20- to 30-minute design storm durations derived solely from assumed minimum time of concentration rules. The observed regional data demonstrates that these assumptions drastically underestimate true storm persistence and total volumetric loads. Local stormwater infrastructure designs should be calibrated against actual rainfall data. It is recommended to implement an evidence-based baseline median duration of 130 minutes for single-peak events, and 298 minutes for complex bimodal events.

(b) Formally incorporate the clipped SCS-SA T1 method: The clipped SCS-SA Type 1 design storm distribution, utilising the Haan *et al.* (1994) extraction technique, should be formally adopted into municipal design guidelines. This method provides the most representative simulation of observed single-peak rainfall intensity distributions and storm volumes without causing the severe intensity distortions of standard unclipped curves.

(c) Integrate the *Bimodal-Split R* method for critical systems: To safeguard catchments against complex, capacity-exceeding rainfall patterns, the *Bimodal-Split R* method should be formally adopted. This methodology should be executed in parallel with single-peak modeling during the hydraulic design and stress-testing of critical attenuation structures, piped reticulation networks, and major drainage infrastructure.

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