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Deriving location-specific synthetic seasonal hyetographs using GPM records and comparing with SCS curves

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ABSTRACT

The hyetograph represents the temporal spread of rainfall intensity occurring at a point or over a watershed during a storm. The importance of regionally derived/developed hyetographs and the pooled sets of categorical seasonal curves on intensity-duration, intensity-depth, and depth-duration are of multifarious conveniences and importance. Twenty-one years of daily and sub-daily rainfall records (2000–2020) regained via satellite-observed precipitation products were examined and used to retrieve a valid understanding towards annual, monthly, daily, and hourly based variability of rainfall across six different stations. An attempt was made to compare the shapes of synthesized seasonal rain mass curves with that of the historic Soil Conservation Service (SCS) mass curve. The results indicate that the location-specific patterns and trends of curves do not align closely with any historical SCS curves or theoretical curves prevalent in the literature and commonly adopted. It has been observed that region-specific rainfall and its temporal distributions exhibit unique trends, not necessarily conforming to the standard SCS-based curves categorized as Types I, Ia, II, and III. This emphasizes the need to rely more on region-specific curves rather than instinctively adopting a standard set of curves.

Key words: climate change, hydrology, hyetograph, rainfall–runoff modelling, SCS curves

HIGHLIGHTS

- Region-specific hyetographs reveal distinct rainfall intensity patterns.
- Historical Soil Conservation Service curve shapes do not align with regional trends.
- Emphasizes the need for region-specific curves over standardized ones.
- Advocates for site-specific mass curves and hyetographs.

INTRODUCTION

The evolution of rainfall depth on the ground for a specific location or over a specific area is often displayed by a hyetograph, which in fact remains an important derivative from the mass curve of accumulated rainfall depth over the storm duration (Kimura *et al.* 2014). It represents the temporal spreading of rainfall intensity occurring at a point or over a watershed during a storm (Chow *et al.* 1988; Yeh *et al.* 2011). Hyetographs have numerous applications; moreover, their unique characterization, both quantitatively and qualitatively, in terms of nature, shapes, patterns, and magnitudes of rainfall mass curves, as well as discrete pulses of rain, often remains highly varied and uncertain for a given point of location and time. Unpredicted changes in the climate and precipitation conditions are widely accepted as one of the prime causes to escalate deterioration of drought and flood occurrences, not only at larger scales/macro-scales but also equally imperative for micro-scales of watersheds, cluster of villages, blocks, or districts in various provinces (Ram *et al.* 2015). It altogether becomes inevitable to deeply seek and understand the spatio-temporal variability of rains from such perspectives.

Researchers have emphasized the importance of mass curves and hyetographs, especially when adopting their non-dimensional forms derived from real observations or stochastic elements (Chow *et al.* 1988; Grimaldi & Serinaldi 2006; Wartalska & Kotowski 2020). Further from hydrological importance, an instantaneous hyetograph can be obtained from the first derivative of the aforementioned hyetograph, specifically for a designated location or time. In the literature, limited design hyetographs have been compared; for instance, in the study by Alfieri *et al.* (2008), the Chicago formulation (Keifer & Chu 1957) appeared to provide the best performance when compared to the variational, rational, and best linear unbiased estimation (BLUE) formulations. As highlighted by Alfieri *et al.* (2008), the Chicago hyetograph may present an excessive rainfall peak intensity about 3.5 times greater than that found using the BLUE approach, 4.2 times greater than with the variational approach, and 7 times greater than with the rational approach. Moreover, these results emphasize that hyetographs presenting constant rainfall intensity tend to underestimate the peak flow, for the rational approach when presenting duration equal to concentration time, while overestimation can occur when adopting the Chicago hyetograph. Similar regional-specific hyetographs for other parts of the globe are the true need of the hour, where a downscaled spatio-temporal scale is carved and the above end deliverables are synthesized. Synthetic hyetographs have emerged as a valuable tool for hydrological modelling and water resource management, as demonstrated in previous studies (Sivapalan *et al.* 2003; Viglione *et al.* 2016; Elhassnaoui *et al.* 2019; Ram *et al.* 2023). These hyetographs can be employed to simulate rainfall events in regions with limited observed data, leading to more accurate estimations of flood risk and design flood hydrographs (Lin *et al.* 2005; Kimura *et al.* 2014; Elhassnaoui *et al.* 2019; Wartalska & Kotowski 2020). Furthermore, they can be utilized to evaluate the impact of climate change on flood risk and enhance the precision of flood forecasting models. Synthetic hyetographs have been shown to provide more accurate estimates of flood risk and design flood hydrographs than traditional methods based on uniform rainfall distribution (Palynchuk & Guo 2011; Chimene & Campos 2020; Al-Wagdany 2021).

The importance of regionally derived/developed hyetographs and the pooled sets of categorical seasonal curves on intensity-duration, intensity-depth, and depth-duration are of multifarious conveniences and importance. These curves, if they become available for finer steps of space and time, may prove to be a significant tool for watershed management, water resource development, irrigation, and drainage planning. They would enhance crop planning, facilitate watershed-based hydrological predictions, and contribute to the design of numerous land and water conservation structures. Two very commonly used rainfall distribution methods are the Natural Resource Conservation Service (NRCS) Method (Soil Conservation Service 1986) and the Huff Distribution Method (Huff 1967). It is well documented in the literature that suitable and accurate hyetographs could be effectually developed using either of these methods. In this course, they used to develop even the region-specific rain mass curves at daily time steps. These mass curves are most commonly, theoretically derived and practically utilized by transforming them into representative storm hyetographs, which can be ultimately used as an input pulse in the majority of rainfall–runoff models. Addressing validation and uncertainty issues and integrating synthetic hyetographs with hydrological models are essential for their practical utility. In addition, ensuring data accessibility and exploring transferability between regions with similar climates can broaden the impact of this research, ultimately facilitating more accurate hydrological assessments and water resource management. The development and application of regionally specific curves can enhance the accuracy of flood forecasting and design, resulting in improved flood risk assessment and mitigation strategies. Consequently, the primary objective of this study was to model the spatio-temporal variability of daily rainfall using historic approaches to establish specific relationships among seasonal hyetographs based on daily rainfall records. This study aimed to develop regionally specific hyetographs and seasonal curves for a data-scarce region utilizing Global Precipitation Mission (GPM) rainfall records. The validity of standard SCS (Soil Conservation Service) hyetographs and curves was assessed for a specific region.

MATERIALS AND METHODS

Data and study locations

Twenty-one years of daily and sub-daily rainfall records (2000–2020) were thoroughly examined and used to retrieve a valid understanding towards annual, monthly, daily, and even hourly based variability of rainfall across six different stations as adopted in the study. Since it involved a huge volume of data and its computerization, only rainy season days (122 days, June to September) were considered while analysing and presenting inferences from them. The key sets of data adopted in this study were regained via satellite-observed precipitation products that are currently available on NASA's web portal for the entire globe (Huffman *et al.* 2019). The GPM serves as the successor to Tropical Rainfall Measuring Mission (TRMM), with Integrated Multi-satellite Retrievals for the Global Precipitation Measurement (IMERG) providing reprocessed data from 2000 to the present; thus, data from 2000 to the latest available year were utilized in this study. The rainfall records were at 30-min temporal resolution and 10 m × 10 m spatial resolution. GPM data was chosen for its high resolution and global coverage, providing accurate and comprehensive rainfall information.

The present study focused on a data-deprived area in middle Gujarat, India. In this area, we identified six closely spaced locations: Gudel and Sojitra villages in Anand district, Kathlal and Dakor in Kheda district, and Pilol and Waghodiya in Vadodara district (Figure 1). These districts have a tropical climate with distinct wet and dry seasons. Monsoons, prevalent from June to September, contribute significantly to the annual rainfall. Mean maximum temperatures range from 28.4 °C in January to 41.8 °C in May, and mean minimum temperatures vary from 11.7 °C in January to 27 °C in June. The region's agricultural dependence underscores the importance of understanding and managing these precipitation patterns.

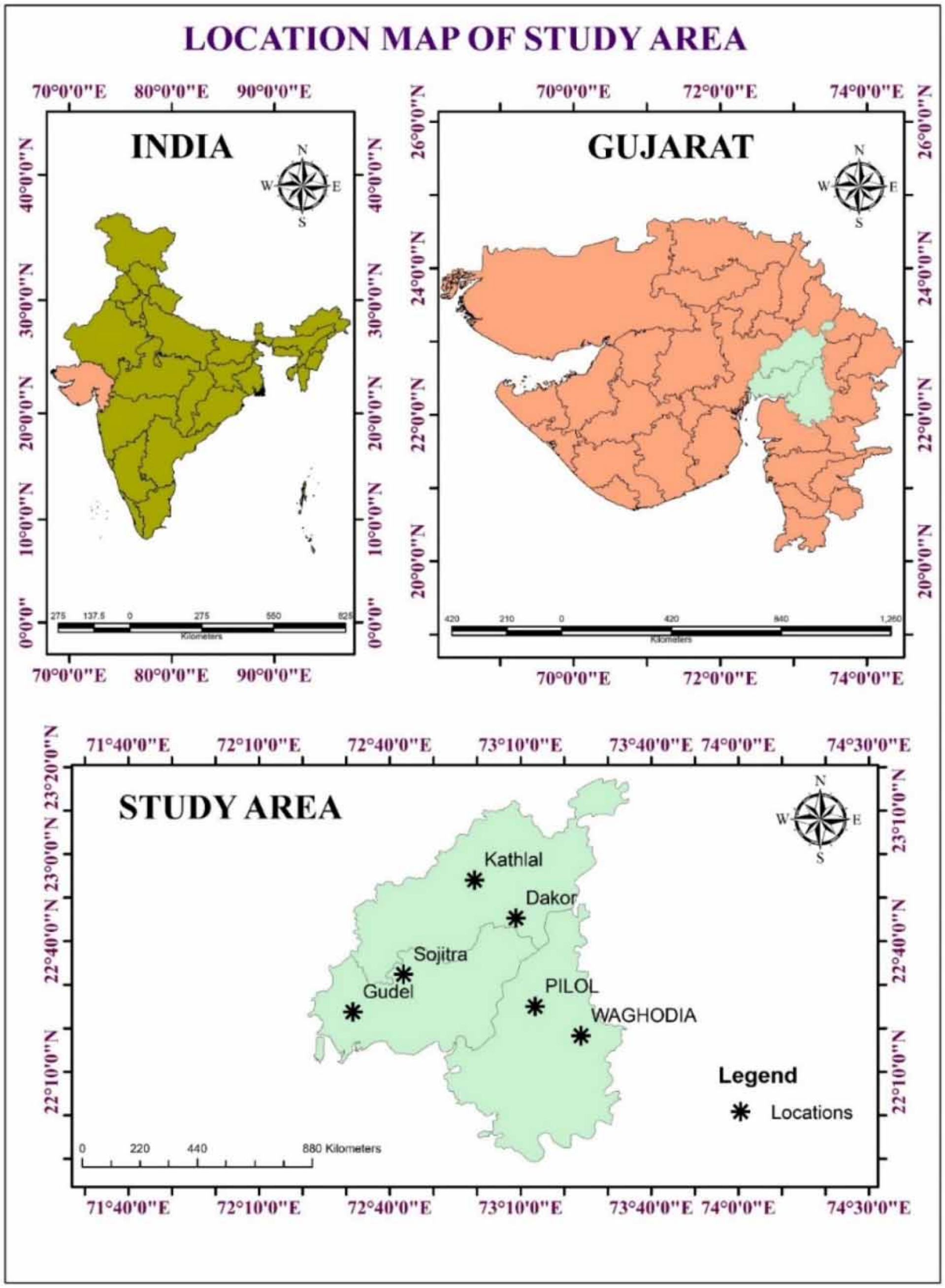

Figure 1 | Map of the study area with village locations.

Deriving synthetic design hyetographs

This study aimed to generate extensive sets of mass curves. These mass curves were then combined into one overall representation. Three specific design mass curves were also developed by selecting from the upper, middle, and lower sections of the combined mass curves envelope. This envelope contains hundreds of observed mass curves from all six stations we studied. These mass curves were formulated and plotted on daily time steps. Looking into a vast number of mass curves of varied depths and durations, an effort was made to transform these envelopes of curves, into their respective dimensionless shape. An average dimensionless mass curve was identified by analysing a range of dimensionless mass curves derived from observed records. This average curve was then employed to create a rainfall hyetograph that serves as a representative design for the specific region or location from which the data were collected.

An attempt was made to compare the ultimate shapes of synthesised seasonal rain mass curves (data driven) with that of historic SCS mass curves (based on four standard time distributions of rains). Three dissimilar dimensionless mass curves from envelopes of curves were retrieved to reflect upper, middle, and lower edges of envelopes of multiple data-driven dimensionless mass curves. An effort was made to plot and compare these three curves for all the six stations with that of standard SCS mass curves (Type I, Type Ia, Type II, and Type III) one by one. The ultimate aim of this exercise was to investigate whether any of the standard SCS shapes closely resembled the data-driven synthetic seasonal design mass curves on a daily time scale.

The SCS developed four synthetic rainfall distributions for a period of 24 h considering a common size of drainage area. Therefore, a single storm duration and associated synthetic rainfall distribution can be used to represent the peak discharges and runoff volumes for a large number of watersheds. Further, the intensity of rainfall varies considerably during a storm as well as geographic regions. The NRCS developed four synthetic 24-h rainfall distributions (I, Ia, II, and III; Figure 2), where Type Ia is the least intense and type II is the most intense short-duration rainfall. The four distributions are shown in Figure 2.

RESULTS AND DISCUSSIONS

A rain mass curve envelope was generated for each station, and a representative averaged mass curve was derived, strategically positioned around the 50% probability of occurrence. It was considered as a representative average mass curve based on real-time rainfall data. The pool of such mass curves is generated for Dakor, Kathlal, Gudel, Sojitra, Pilol, and Waghodiya as shown in Figures 3 and 4. These curves reflected 21 years wide spectrum of observed rains at daily time step for elapsed duration of about 122 days, i.e., one complete monsoon season (July–October). An in-depth exploration of the amassed data reveals the astonishing breadth of the observed mass rainfall ranges at each station over the 21-year span. Dakor experienced fluctuations ranging from 429 to 1,833 mm, while Kathlal encountered variations from 450 to 1,778 mm. Gudel's range spanned from 469 to 1,738 mm, Sojitra witnessed a remarkable spectrum between 453 and 18,000 mm, Pilol observed

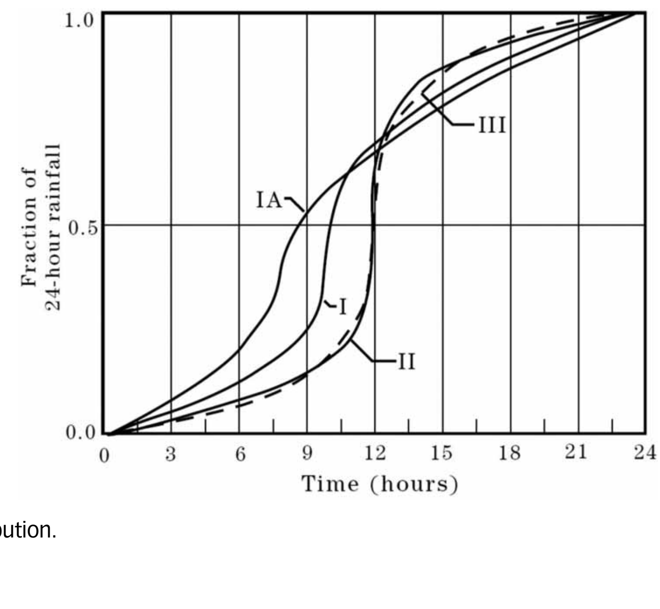

Figure 2 | SCS 24 h rainfall distribution.

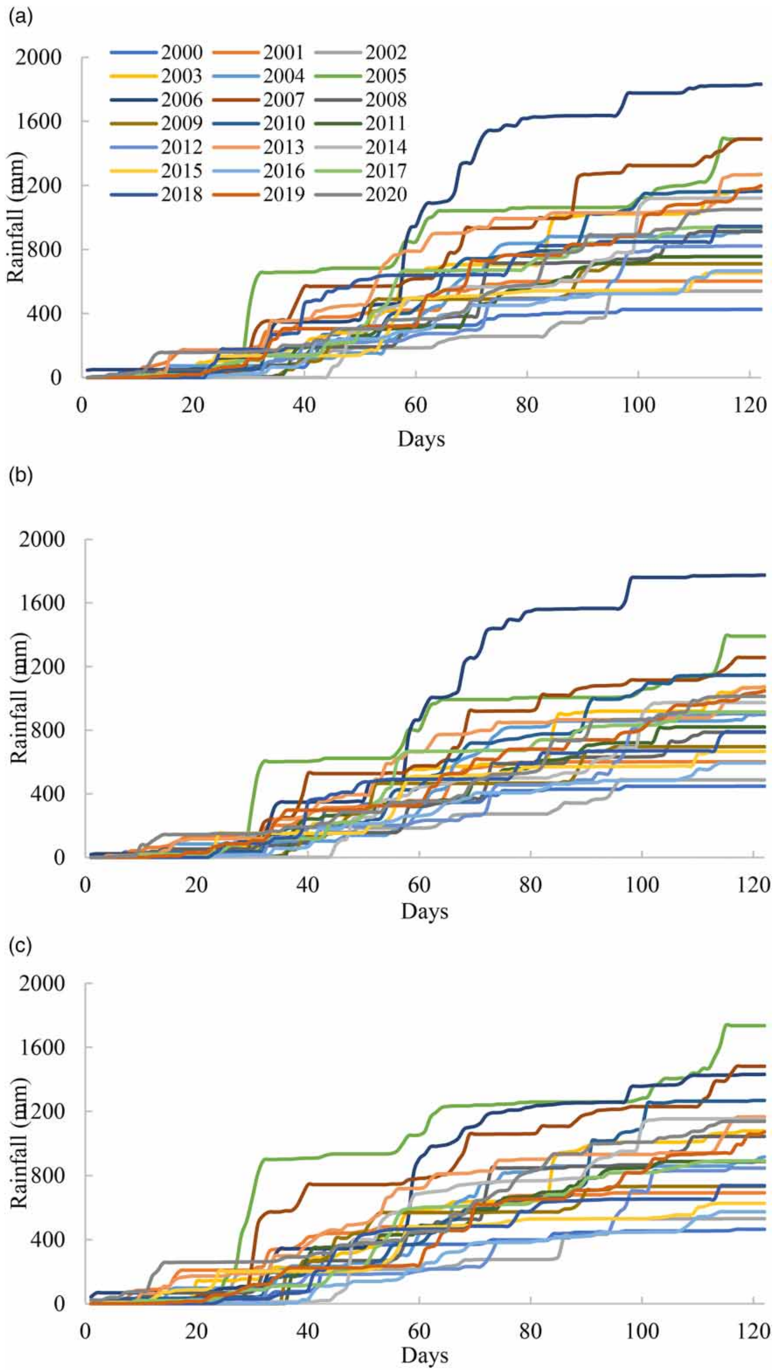

Figure 3 | Envelope of actual rain mass curves: (a) Dakor, (b) Kathlal, and (c) Gudel.

variations from 476 to 1,860 mm, and Waghodiya exhibited a range extending from 491 to 1,660 mm. Notably, the year 2006 emerged as a meteorologically anomalous period, characterized by the occurrence of the most intense rains across all stations, a phenomenon that stands out conspicuously in the dataset.

The subsequent phase of the study delved into the creation of dimensionless standard mass curves, meticulously depicted in Figures 5 and 6. These curves not only serve as a representation of the overall shape function of the rainfall mass curve but also offer a nuanced understanding of their functional characterization. The intricate patterns and subtle variations encoded in these curves provide valuable insights into the underlying meteorological processes governing rainfall in the region. The

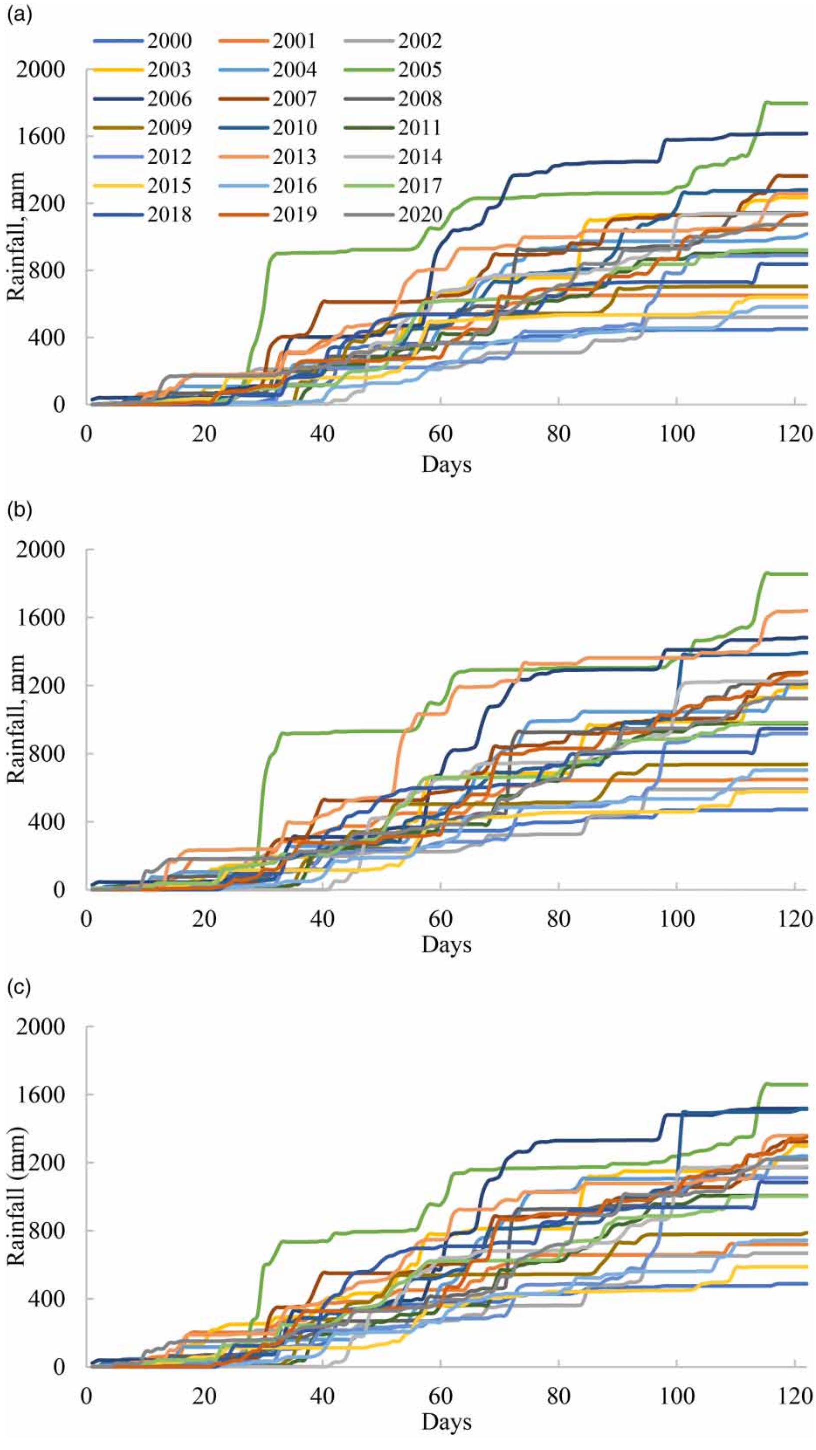

Figure 4 | Envelope of actual rain mass curves: (a) Sojitra, (b) Pilol, and (c) Waghodiya.

synthesis of this extensive dataset culminated in the development of six synthetic design hyetographs, as eloquently portrayed in Figure 7. This visual representation brings to the fore the temporal and intensity variabilities inherent in the rainfall patterns, offering a comprehensive view of the regional dispersal of these climatic attributes. The distinctiveness of each hyetograph underscores the complexity of the relationship between time and rain intensity, highlighting the need for a region-specific approach to understanding and modelling these phenomena.

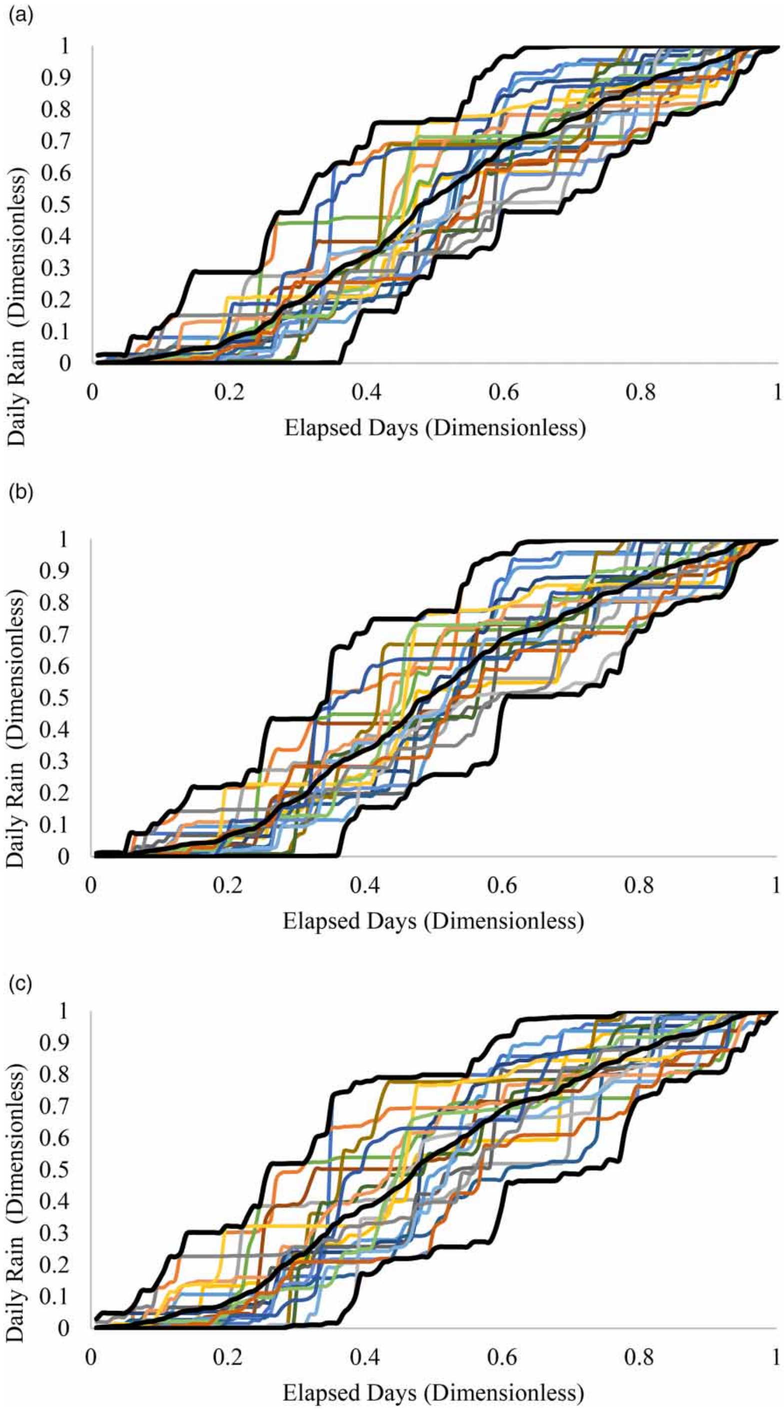

Figure 5 | Envelope of dimensionless rainfall mass curves: (a) Dakor, (b) Kathlal, and (c) Gudel.

Comparison of seasonal mass curve with standard SCS curves

Results show that out of four only one, i.e., Type Ia, matches up to a certain extent (partially on time span); moreover, the extent of similarity in shapes was found significantly dispersed for different durations and locations. An attempt was made to quantitatively compare the partial matching status of the above quoted curves. It was found that for the initial 35–45% elapsed time, there remained a good match in the shape of seasonal mass curve with Type Ia SCS curve; but beyond this point, there emerged significant over-estimations in comparison to SCS Type Ia. This result remains valid for all the six

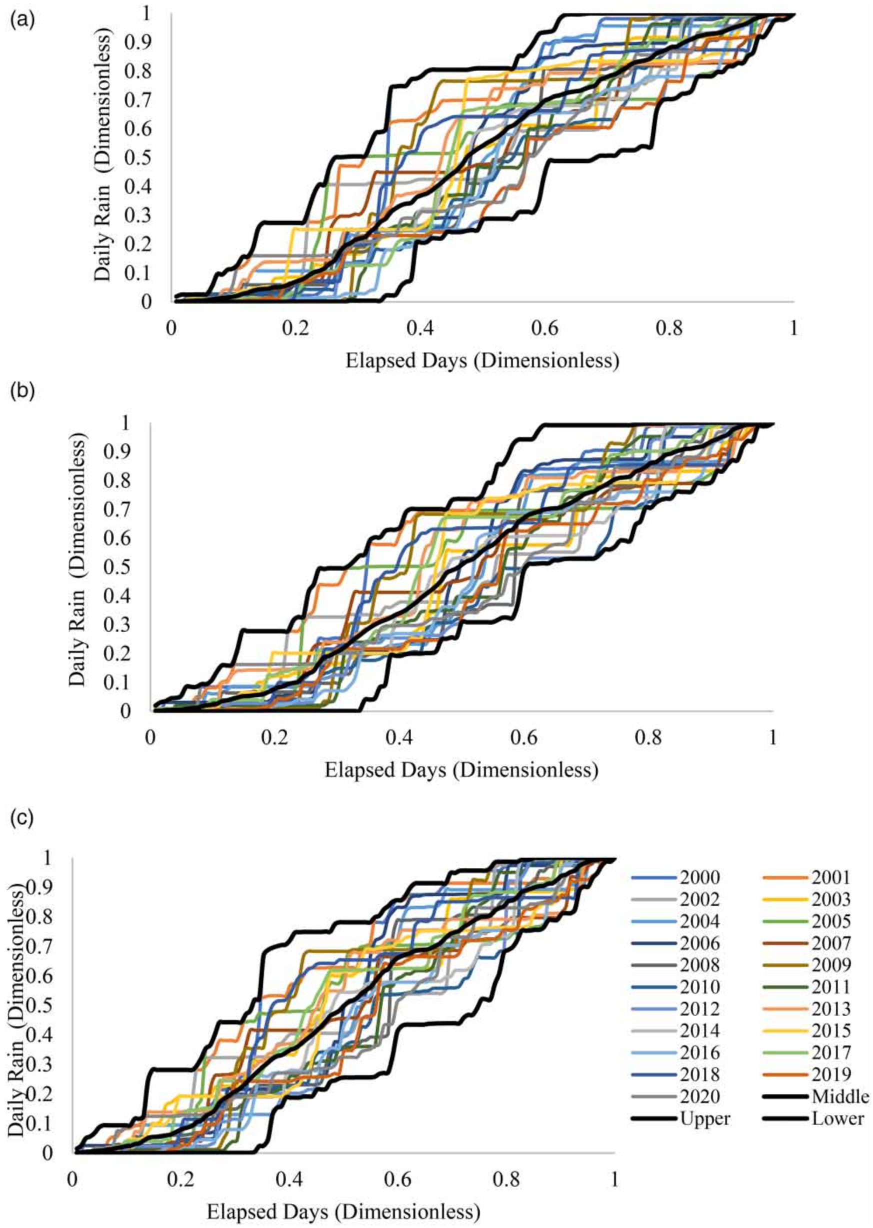

Figure 6 | Envelope of dimensionless rainfall mass curves: (a) Sojitra, (b) Pilol, and (c) Waghodiya.

stations, but in a varied magnitude of dispersals. The overall comparisons of shapes of these three synthetic seasonal design mass curves for all the six stations are shown in Figure 8, where a single SCS Ia curve is superimposed over them, just to depict the magnitude of negative or positive dispersals (along timeline) of developed curves in regards to this.

The findings of the present study conform with those of many of the researchers. Powell *et al.* (2007) found noticeable variances temporal characteristics of rain storms as compared to that of SCS curve castoff in their study region. El-Sayed (2018) developed synthetic rainfall distribution curves and compared to the standard SCS profiles type curves, where a significant difference was found while computing runoff between their approach with that of NRCS-SCS distributions. Awadallah *et al.* (2017) developed storm profiles and compared to the frequently used SCS dimensionless distributions and the UK50 (NERC 1975) storm profiles, and it was found that SCS- and UK50-based design rain curves are not safe to be used in the design of hydraulics structures in arid and hyper arid regions. Instead, they recommended the use of regionally derived hyetographs based on the actual records of historic storms. Elfeki *et al.* (2014) derived design storm

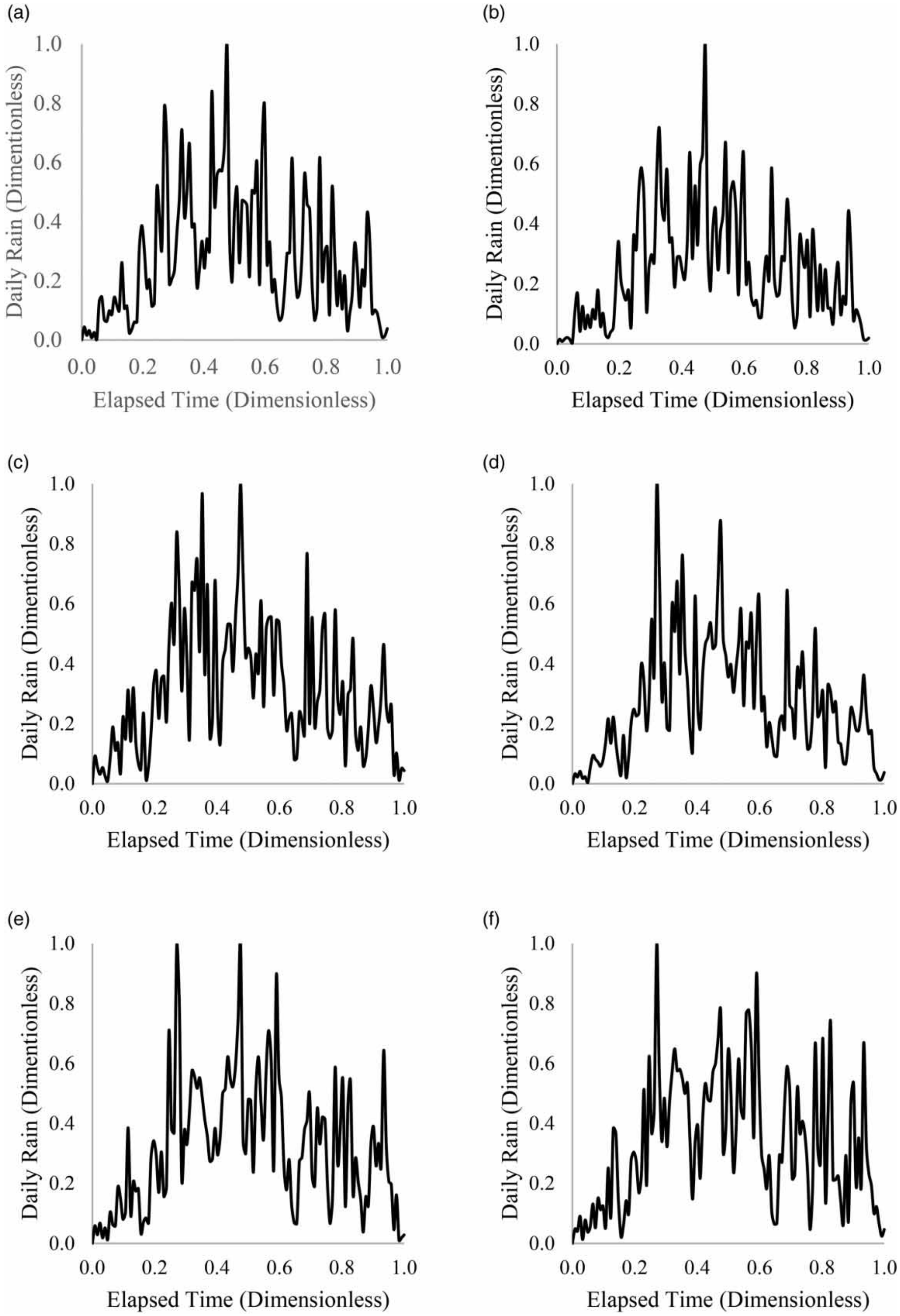

Figure 7 | Synthetic seasonal design hyetographs for six stations: (a) Dakor, (b) Kathlal, (c) Gudel, (d) Sojitra, (e) Pilol, and (f) Waghodiya.

hyetograph patterns based on observed rainfall events in the Kingdom of Saudi Arabia. The authors observed that the developed storm hyetographs have different features from other storm patterns that are commonly used in the study region, and hence, they recommended to use regionally derived/developed storm hyetographs for the design of hydrologic or hydraulic structures in study locations.

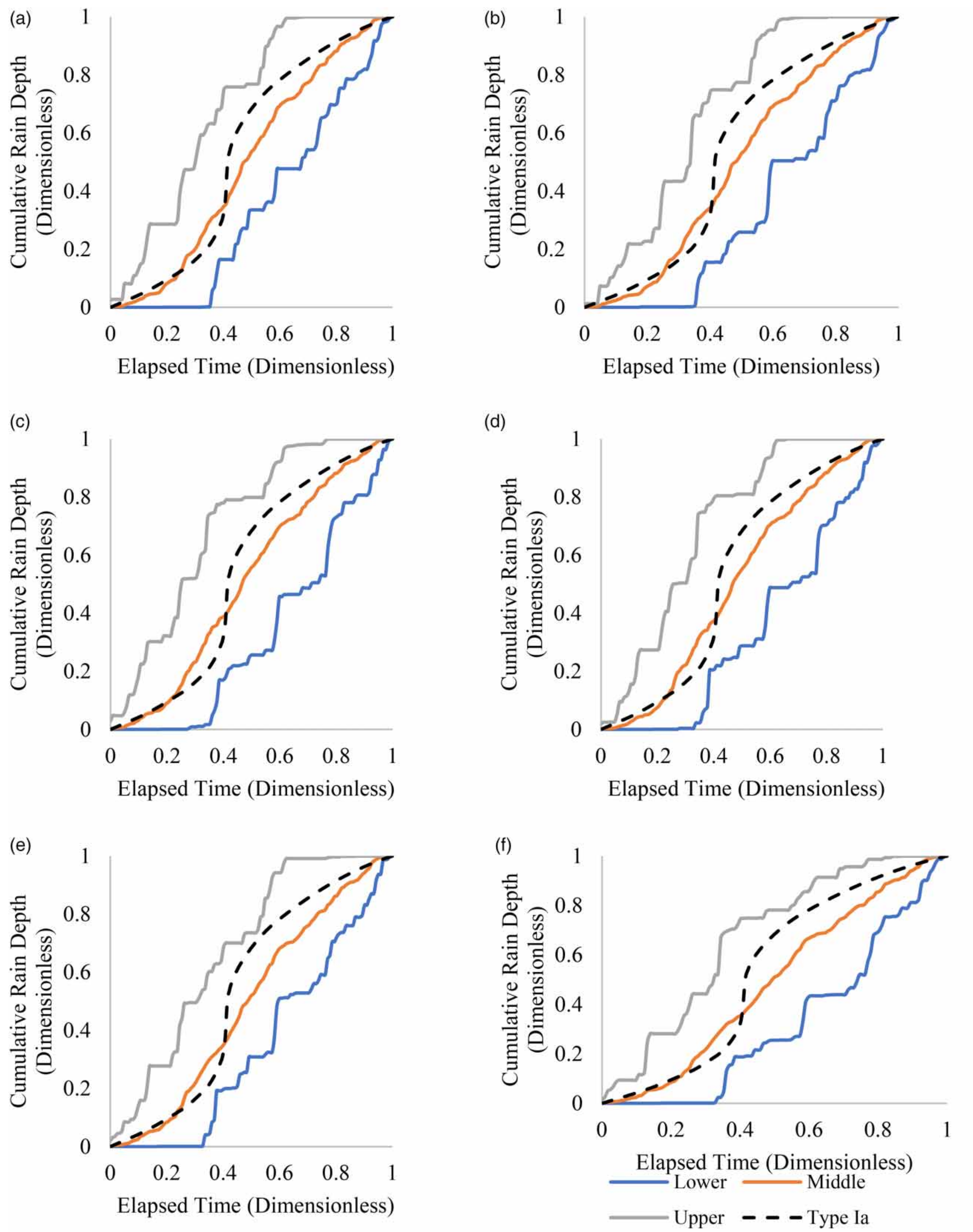

Figure 8 | Matching shapes of actual average daily mass curves with standard dimensionless SCS curves: (a) Dakor, (b) Kathlal, (c) Gudel, (d) Sojitra, (e) Pilol, and (f) Waghodiya.

CONCLUSION

The scarcity of hourly rainfall data presents a consistent challenge in water sector research and development. Despite difficulties in obtaining high-resolution satellite precipitation data, traditional hyetographs and rainfall mass curves remain crucial for precipitation analysis. In the absence of finer data, researchers and water managers often use daily rainfall data for its versatility, including generating input hyetographs for rainfall–runoff models and water balance assessments, particularly for larger catchments and basins. Research outcomes emphasize that region-specific rainfall patterns have unique temporal trends, not necessarily aligning with standard SCS-based curve shapes (Types I, Ia, II, and III). This underscores the need for tailored approaches in understanding and modelling regional rainfall variability, shifting towards reliance on region-specific curves rather than automatically adopting standardized sets. The study validates the utility of seasonal synthetic design mass curves in the region, enhancing their applicability in water-related research and ground-based applications. Results indicate that location-specific curve patterns significantly differ from historical SCS curves and theoretical curves, highlighting the distinctiveness of regional rainfall behaviour. These findings serve as a resounding reminder and a compelling call to action. They underscore the necessity of moving away from the traditional, historical approaches to rainfall excess computations and estimations, which often rely on coarse time-step data, primarily daily, or interpolated/extrapolated values. The results of this study offer a promising avenue for raising awareness, generating interest, and promoting the earnest adoption of site-specific mass curves or hyetographs. This approach holds particular significance in the context of agricultural water planning and management, especially during the monsoon or rainy season. It presents an opportunity to enhance the precision and effectiveness of water resource strategies, ushering in a new era of informed decision-making. The dependability of the regional hyetograph method is significantly influenced by the quality and accessibility of the data employed for the development of synthetic design mass curves. In regions with sparse or unreliable historical rainfall data, the accuracy of the curves may be compromised. The synthetic design mass curves might not capture fine-scale variations, especially in areas with diverse topography or complex weather patterns.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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