

# Peak discharge estimation in data-scarce regions: a comparative study of methods for Syrian ungauged basins

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**Abstract:** Accurate estimation of peak discharges in small, ungauged basins is critical for flood risk management, particularly in developing countries where hydrometeorological data are scarce. This study compares empirical/conceptual methods (Fuller's formula, Rational Method), event-based models (EBA4SUB), and continuous modeling (COSMO4SUB) across three Syrian catchments. Results show that empirical approaches are highly sensitive to parameter selection and often underestimate peak discharges, while event-based models, though more flexible, remain influenced by user-defined assumptions such as hyetograph shape and antecedent moisture conditions. The COSMO4SUB continuous modeling approach provides a robust alternative, reducing subjective choices and better representing physical catchment processes, including soil saturation, runoff generation, and temporal rainfall variability. These features make COSMO4SUB particularly suitable for data-scarce environments, offering a reliable tool for flood estimation, infrastructure design, and resilience planning.

*Keywords: COSMO4SUB; Data Scarcity; EBA4SUB; Flood Estimation; Rainfall-Runoff Modeling; Syria; Ungauged Basins*

## Introduction

Reliable estimation of design hydrographs and their key properties—such as peak discharge, total runoff volume, and event duration—is a fundamental requirement for effective water resources management and infrastructure planning, particularly in flood-prone and hydrologically sensitive regions (Ayalew et al., 2022; Gadek et al., 2022). This challenge is even more pronounced in small, ungauged basins common in developing countries, where data scarcity coincides with high flash-flood risk (Grimaldi et al., 2021; Behery et al., 2025). In arid and semi-arid regions such as the Middle East, short-duration intense rainfall events exacerbate vulnerability, making reliable hydrological estimates critical (Luong et al., 2020; Shawky and Hassan, 2023).

Design hydrographs, which describe the temporal evolution of runoff generated by a specific rainfall event, are essential for designing flood defenses, culverts, reservoirs, and other hydraulic structures (Młyński et al., 2020a; Lee et al., 2025). In developing countries—where rapid urbanization, land-use changes, and increasing climate variability

complicate hydrology—the estimation of hydrographs in small, ungauged catchments is particularly challenging. Regionalization approaches, transferring information from gauged to ungauged basins, are therefore crucial (Merheb et al., 2016; Pool et al., 2021).

Syria exemplifies these difficulties. Its semi-arid climate features highly variable rainfall concentrated in a short season, while its topography—from western mountains to eastern plains—produces diverse hydrological responses (Merheb et al., 2016; Zeleňáková et al., 2022). In small, remote catchments, the lack of gauging stations creates critical data gaps (Shaddoud et al., 2025a; 2025b). Similar flash-flood patterns are observed in Mediterranean basins of neighboring countries (De Vries et al., 2013; Peleg et al., 2015), and their estimation is particularly complex.

For instance, Alipour and Kibler (2019) examined the performance of regionalization techniques and model transferability in hydrologically heterogeneous regions. They showed that when applying models to less gauged or drier basins, the efficacy of parameter transfer declines, especially when donor basins differ in climate or aridity. This warns that approaches relying heavily on donor basin similarity may not perform well in semi-arid, ungauged settings. Bat-Erdene et al. (2025) focused on sustainable hydrological or water-resource modeling under conditions of limited data and environmental stress (e.g. aridity, land use change). The study underscored how assumptions and simplifications (such as uniform parameter values or static relationships) can introduce large uncertainties when applied to semi-arid basins that are ungauged, where local variability is high and calibration data are scarce. Santana et al. (2025) investigated advanced hydrological modeling frameworks for basins with poor data coverage, emphasizing how continuous and hybrid models may better account for temporal rainfall dynamics, antecedent moisture, and basin responsiveness. However, the study also critiqued these methods by showing that their performance is sensitive to the quality and resolution of input data—something often lacking in semi-arid, ungauged basins—and cautions about overfitting or misrepresentation when local calibration is limited. Together, previous studies converge on the message that modeling in ungauged, semi-arid basins is especially challenging. Parameter transfer or empirical simplifications risk large errors, and more sophisticated continuous or hybrid models are promising but must contend with data scarcity, input uncertainty, and the need for robust calibration strategies.

In Syria, the problem is compounded by decades of conflict that have degraded hydrometeorological infrastructure, leaving many areas without reliable rainfall or streamflow records (UNECE, 2023). This situation reflects broader challenges in developing countries, where institutional, financial, and technical constraints limit hydrological monitoring and modeling capabilities (Hammouri and El-Naqa, 2007; Comair et al., 2013). In such data-scarce environments, empirical methods—like regional regressions or simplified runoff formulas—dominate due to their minimal data requirements (Petroselli et al., 2020a; Młyński et al., 2020b).

In Syria, empirical methods have been adapted locally, yet their reliance on historical data and assumptions of stationarity limits their reliability in small, heterogeneous basins (Zhao et al., 2024; Ghaneei et al., 2024). Local factors—such as soil, slope, land cover, and rainfall intensity—strongly influence runoff responses, making simple formulas potentially misleading. Overreliance on these techniques risks underestimating flood hazards and misinforming infrastructure design. Statistical approaches, including frequency analysis of peak flows and synthetic unit hydrographs, have also been applied, but these require long-term records, which are absent in ungauged basins, and generally neglect physical hydrological processes (Ganora et al., 2023; Abdelkarim et al., 2025).

Rainfall-runoff modeling provides an alternative for simulating runoff where measurements are lacking. Simple methods, such as the Rational Method, remain widely used but rely on generalized assumptions (McIntyre and Al-Qurashi, 2009; Petroselli et al.,

2020a; Hussein et al., 2024). Event-based models better capture spatial variability and catchment processes, though they still require parameter estimates through regionalization or indirect calibration (Petroselli et al., 2020b; Huynh et al., 2023). Continuous simulation methods offer higher physical realism by accounting for antecedent moisture, evapotranspiration, and seasonal dynamics, but they are data-intensive, technically complex, and difficult to implement under the constraints typical in developing countries (Perrin et al., 2001; Grimaldi et al., 2012a; 2021).

Despite these methodological options, major gaps remain in accurately estimating design hydrographs in small, ungauged Syrian basins and similar settings. Comparative studies are scarce, and the combined effects of data scarcity, climate variability, and land-use change remain underexplored (Zhao et al., 2024). There is a clear need for innovative, data-efficient modeling strategies that balance empirical simplicity with physical realism. Exploring hybrid approaches is essential to enhance flood resilience and support evidence-based planning in small catchments (Sivapalan et al., 2003; Peleg et al., 2015).

Building on this context, the present study systematically compares methodologies currently applied in Syria—including empirical and conceptual—and evaluates their performance against recent rainfall-runoff models, like EBA4SUB (Event-Based Approach for Small and Ungauged Basins) (Piscopia et al., 2015; Petroselli and Grimaldi, 2018) and COSMO4SUB (Continuous Simulation Model for Small and Ungauged Basins) (Grimaldi et al., 2021, 2022). Both EBA4SUB and COSMO4SUB have been designed for small basins that are ungauged or with very limited flow data, require minimal input data requirements, and are characterized by an empirical-conceptual hybrid structure like explained in the following.

While flood risks in such basins are increasingly recognized, few studies focus on Syria's semi-arid, data-scarce conditions. Existing methods often rely on oversimplified assumptions or require data beyond local availability, and comparative evaluations are limited. This study addresses these gaps by testing a range of approaches and offering a data-efficient framework for flood estimation in challenging environments.

## **Materials and Methods**

### *Case Studies and available data*

Three river basins were selected for this study, each representing distinct hydrological and geomorphological characteristics within the coastal region. The case studies are the Abrash basin, the Haffa Sub-basin of Al-Kabir Al-Shamali Basin, and the Al-Sinn Basin (Figure 1).

The first case study focuses on the Haffa sub-basin, that is a part of the Al-Kabir Al-Shamali Basin and that contributes directly to the formation of the Haffa Dam reservoir. Key characteristics include a contributing area of 60.2 km<sup>2</sup>, a main channel length of 21.5 km, an average channel slope of 5%, an average basin slope of 22%, and an average basin elevation of 786 m. The Haffa Sub-basin is characterized by sparse shrubs and scattered small forests, typical of limestone uplands. Agriculture is limited, though minor grazing or orchards may be present. The soils here are shallow to moderate, developed over limestone, and consist mainly of Calcaric Leptosols, Cambisols, or Arenosols, which are typical of Mediterranean karst landscapes. These soils are stony, well-drained, and low in organic matter, often overlaying a rocky substrate. The Haffa Dam, with a storage capacity of 1.5 million cubic meters, is used primarily for potable water supply. The basin receives an average annual rainfall of 1,640 mm, and the mean annual temperature is 17.5°C.

The second case study is the Al-Sinn Basin, a watershed primarily fed by the Al-Sinn Spring, a major karstic water source discharging at an elevation of about 6 meters above sea level, approximately 6 km inland from the Mediterranean coast. The spring's flow path extends about 3.5 km to a downstream gauging station. The basin is bounded by the Al-Sakhaba watershed to the north, the Harisson watershed to the south and east, and the Mediterranean Sea to the west. The Al-Sinn Spring is a critical freshwater source, utilized for drinking water, agriculture, aquaculture, and industrial use. During flood periods, excess discharge flows directly into the sea. Key characteristics include a contributing area of 87 km<sup>2</sup>, a main channel length of 28.7 km, an average channel slope of 4%, an average basin slope of 25% and an average basin elevation of 400 m. In the Al-Sinn Basin, the land cover is likely to consist of riparian grassland or shrubland near the spring and its downstream reach, with limited agricultural or irrigated areas near the spring headwaters. The region around the spring discharge channel may support denser vegetation, such as reeds or irrigated crops, if present. The soils in the basin are predominantly shallow and carbonatic, such as Leptosols formed over limestone. Closer to the spring-stream channel, fluvisols or gleyic soils may be found in alluvial deposits, where water overflow interacts with the soil, potentially enriching it with organic material. The basin receives an average annual rainfall of 1,113 mm, and the mean annual temperature is 18.5°C.

The third case study is the Abrash Basin, located in the southern part of the coastal region and drained by the Abrash River, one of the most significant seasonal watercourses in the area. The basin has an elongated shape, bounded by the Ghamqa River Basin to the north and the Al-Kabir Al-Janoubi River Basin to the south and southeast. The river originates on the western slopes of the coastal mountain range at an elevation of approximately 750 meters. Key characteristics of the basin include a contributing area of 248.8 km<sup>2</sup>, a main channel length of 46.7 km, an average channel slope of 1.9%, an average basin slope of 14%, and an average basin elevation of 451 m. The Abrash River flows southwest and enters the Mediterranean Sea approximately 3 km south of the village of Al-Hamidiyah. The Abrash River is classified as a seasonal (intermittent) watercourse, meaning it experiences prolonged periods of no flow (cessation of flow) during the dry season, in contrast to perennial rivers, which maintain flow year-round. This characteristic is typical of many catchments in the semi-arid Mediterranean region. The river course is meandering, with steep slopes in certain sections (up to 4%-5%). The Abrash Basin is predominantly sparsely vegetated, with low shrubs and rocky or bare soils. Olive groves can be found in localized areas, mainly in the southern part of the basin, where they are largely unmanaged or semi-cultivated. The soils in this basin are typically stony and shallow to moderately deep, often rooted in limestone and calcareous sedimentary bedrock. These soil types include Leptosols or Calcaric Cambisols/Arenosols, depending on local lithology and depth. The surface is marked by rocky outcrops, coarse pebbles, and coarse-textured layers, which limit soil depth and organic content. The Al-Basel Dam, constructed on the Abrash River, has a storage capacity of 103 million cubic meters. The region receives an average annual rainfall of 1,461 mm, and the mean annual temperature is 18°C.

For all three selected case studies, a Digital Elevation Model (DEM) with a 30-meter resolution, along with land use and soil type maps, was provided by the Syrian Ministry of Water Resources. The Ministry oversees the management and protection of the country's surface and groundwater resources. Its agencies, such as the General Commission for Water Resources and regional Water Directorates, collect vital geospatial data—like digital elevation maps—used to plan hydrological projects, model river basins, and manage flood control. Rainfall data from gauges located within the studied watersheds were also acquired and analyzed. Rainfall data were collected with the support of the Syrian General Directorate of Meteorology (GDM). The GDM operates and maintains an extensive network of meteorological stations across the country. It provides daily, monthly, and

annual precipitation records, which are essential for water balance assessments and drought studies. These records also serve as key inputs for hydrological models. Specifically, daily cumulative rainfall records were available from January 1, 2009, to December 31, 2022—a continuous 14-year dataset with no missing values. This comprehensive dataset enabled the development of Depth-Duration-Frequency (DDF) curves using the Gumbel distribution method. The analysis was based on the assumption that the relationship between rainfall duration and cumulative depth for short-duration events (a few hours) follows the same statistical distribution as that of events with durations exceeding one day.

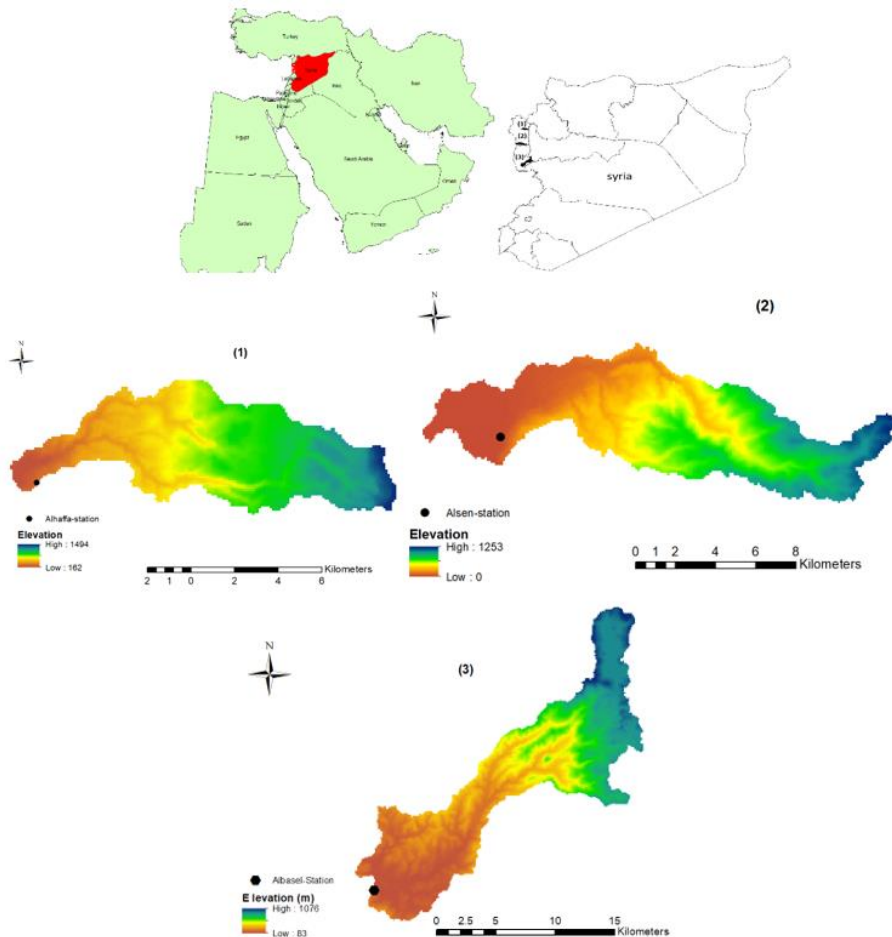


Figure 1. Case studies localization. General localization of Syria and of the investigated case studies within Syria; (1) Haffa sub-basin; (2) Al-Sinn Basin; (3) Abrash Basin. Black points indicate the rain gauge stations.

### The employed methodologies

#### The rational formula

The Rational Formula (Mulvaney, 1851) is one of the simplest and most widely used methods in rainfall-runoff modeling, typically used for small catchments or urban areas with limited data. The formula expresses the peak runoff rate  $Qp$  ( $m^3/s$ ) as a function of the rainfall intensity  $I$  ( $mm/h$ ), the catchment area  $A$  ( $km^2$ ), and a runoff coefficient  $C$  (-), which accounts for land use and soil conditions:

$$Qp = \frac{CIA}{3.6} \quad (1)$$

Advantages of the Rational Formula include its simplicity, ease of use, and relatively low data requirements, making it ideal for small to medium-sized watersheds, particularly in regions with limited hydrological data. It is also adaptable to both urban and rural settings. However, although the method is diffuse, its drawbacks are well recognized and documented in literature (Grimaldi and Petroselli, 2014). One of the key issues is the subjectivity in determining the runoff coefficient, which often comes as a range rather than a fixed value. This introduces uncertainty, as the coefficient can vary based on land use, soil conditions, and other factors, leading to potential inaccuracies. Additionally, the formula does not consider physical variables such as ponding time, infiltration rates, or the temporal distribution of rainfall, which are crucial in accurately modeling runoff, particularly in more complex or large catchments. These limitations make the Rational Formula less reliable in regions with heterogeneous terrain, varying rainfall patterns, or where detailed hydrological processes need to be accounted for.

In the context of Syria and the Middle East, the Rational Formula has been applied in various hydrological studies and infrastructure projects, especially for urban flood control and water resource management. In these areas, the formula has helped in designing drainage systems and assessing the impacts of urbanization on runoff. However, in regions with highly variable terrain and seasonal rainfall, the formula's assumptions can limit its accuracy, prompting the need for more sophisticated models or calibration with local data (Al Sawalqa et al., 2020; Hifa and Irsak, 2024)

#### ***The Fuller's method***

The Fuller empirical formula, developed in the eastern U.S. based on flood peak analysis (Fuller, 1914), is widely used globally to estimate maximum flood peaks, since it provides a straightforward way to estimate peak discharges using minimal input data, making it especially useful in regions with limited monitoring infrastructure. The Fuller empirical formula is expressed as it follows:

$$Q_p = Q_{max}(1 + 11.63 A^{-0.31278}) \quad (2)$$

$$Q_{max} = Q_{ave}(1 + B * \log(T)) \quad (3)$$

$$Q_{ave} = CF * A^{0.8} \quad (4)$$

where  $Q_p$  (m<sup>3</sup>/s) represents the maximum instantaneous peak flow associated with a return period of  $T$  years,  $Q_{max}$  (m<sup>3</sup>/s) is the maximum daily discharge for the same return period  $T$ ,  $Q_{ave}$  (m<sup>3</sup>/s) is the average maximum daily discharge of basin,  $A$  is the watershed area (km<sup>2</sup>),  $CF$  (-) is a regional coefficient that accounts for the climatic, geographical, and basin characteristics, and  $B$  (-) is the regional inundation frequency coefficient.

The Fuller formula, originally developed in the eastern United States, has been adapted and applied in numerous regions around the world, including widespread use in the Middle East. In this region, where hydrological data can often be scarce or unevenly distributed, the formula's empirical nature and relatively simple structure have made it a practical tool for flood estimation. Its coefficients have been calibrated to reflect local climatic, topographic, and hydrological conditions, with multiple studies confirming its applicability across various watersheds (Sazabpardazan, 2006; Salajegheh and Dastorani, 2006).

The method's key advantages lie in its simplicity, speed of application, and flexibility. Because its empirical coefficients can be adjusted for local conditions, it offers reasonably accurate flood peak predictions when properly calibrated. This adaptability has made it a preferred choice in Middle Eastern hydrological studies, particularly in Iran, where it has been applied across numerous basins. However, despite these benefits, the method also

presents notable limitations. One of the primary concerns is its sensitivity to calibration: the regional coefficients can vary widely depending on local environmental factors, requiring careful adjustment to avoid significant errors. Moreover, the Fuller formula is designed specifically for estimating peak discharges and does not incorporate other important hydrological processes such as infiltration, soil moisture variation, land use change, or evapotranspiration. As a result, it may overestimate flood peaks, particularly for high return periods or in humid sub-regions where more complex runoff processes dominate. For these reasons, while the Fuller formula remains a valuable tool in Middle Eastern hydrology, it must be applied with a clear understanding of its empirical nature and the regional context in which it is used.

### **EBA4SUB**

The EBA4SUB (Event-Based Approach for Small and Ungauged Basins) model is a conceptual framework designed for simulating rainfall-runoff processes in small, data-scarce catchments (Piscopia et al., 2015; Petroselli and Grimaldi, 2018). Based on a single-event approach, it is suitable for basins typically under a few hundred square kilometers, where rainfall distribution can be considered uniform. The model is structured in three main phases: gross rainfall identification, excess rainfall estimation, and runoff calculation.

In the first step, Depth-Duration-Frequency (DDF) curves are used to estimate cumulative rainfall depths for various return periods  $T$ , assuming the catchment concentration time, that was estimated here using the Giandotti formula (1934), as the critical rainfall duration. The Chicago hyetograph (Keifer and Chu, 1957) is then applied to define the temporal distribution of the design rainfall (Petroselli and Grimaldi, 2018). In this work, the commonly used 2-parameters DDF equation is used, as described below.

$$P = a * t^n \quad (5)$$

Where  $P$  (mm) is the cumulative rainfall depth,  $t$  (h) the rainfall duration (in general equal to the watershed concentration time), and  $a$  (mm/h) and  $n$  (-) the DDF parameters as function of the return period.

In the second step, for estimating excess rainfall, the Curve Number for Green-Ampt (CN4GA) method was applied. CN4GA is a hybrid model combining the NRCS Curve Number (CN) method (NRCS, 2008) with the Green-Ampt infiltration model (Green and Ampt, 1911), as proposed by Grimaldi et al. (2013). CN4GA method uses first the CN method to determine initial abstraction and total excess precipitation, and then applies the Green-Ampt model to distribute this excess over time, automatically using soil data and calibrating hydraulic conductivity to match observed runoff volumes. In detail, the CN method is used by CN4GA to estimate the onset of ponding and quantify cumulative runoff, as described below.

$$P_n = \begin{cases} \frac{(P-Ia)^2}{P+S-Ia} & \text{for } P \geq Ia \\ 0 & \text{for } P < Ia \end{cases} \quad (6)$$

where  $P_n$  is the cumulative excess rainfall (mm),  $P$  is the cumulative rainfall depth provided by DDF curves (mm),  $S$  is the maximum potential retention of the watershed (mm), and  $Ia$  (mm) is the initial abstraction accounting for interception, infiltration, and surface storage (mm). In this study, the original assumption of the SCS-CN method was applied, with the initial abstraction  $Ia$  set equal to 0.2 times the watershed's maximum potential retention ( $S$ ), where  $S$  is a function of the Curve Number (CN), which is

essentially the sole parameter of the method. In the second phase of the CN4GA procedure, the temporal dynamics of excess rainfall are addressed using the Green-Ampt (GA) infiltration model. This approach provides a more physically based representation of how excess rainfall develops over time, as described below.

$$q_0(t) = \begin{cases} i(t) & \text{for } t < t_{\text{pond}} \\ K_s \left(1 + \frac{N_s}{F(t)}\right) & \text{for } t > t_{\text{pond}} \end{cases} \quad (7)$$

where  $q_0(t)$  is the infiltration rate,  $t_{\text{pond}}$  is the ponding time,  $F(t)$  is the cumulative infiltration,  $K_s$  is the saturated hydraulic conductivity, and  $N_s$  is the moisture-tension parameter. Equation (7) assumes that ponding occurs when cumulative precipitation  $P(t)$  first equals the initial abstraction  $I_a$ . The saturated hydraulic conductivity  $K_s$  is then automatically calibrated to ensure that the total cumulative excess rainfall estimated using the Green-Ampt model aligns with the net runoff calculated via the NRCS-CN method. The remaining Green-Ampt parameters are derived from the soil properties of the study area, using standard reference values corresponding to the identified soil type.

In the third step, surface runoff is derived from excess rainfall using the Width-Function Based Instantaneous Unit Hydrograph (WFIUH), generated directly from the study area's DEM. After ensuring hydrological consistency by removing depressions and flats and delineating the drainage network (with a 1 km<sup>2</sup> threshold), travel times are computed based on watershed geomorphology. The WFIUH is then constructed following the method of Grimaldi et al. (2012), as described in the equation below.

$$WFIUH(t) = \frac{L_c(x)}{v_c(x)} + \frac{L_h(x)}{v_h(x)} \quad (8)$$

where  $L_c$  and  $L_h$  are the lengths of the flow path for channel and hillslope cells  $x$  in the DEM, and  $v_c$  and  $v_h$  are the corresponding surface flow velocities. Once the WFIUH is defined, runoff  $Q(t)$  is computed as follows:

$$Q(t) = A \int_0^t WFIUH(t - \tau) P_n(\tau) d\tau \quad (9)$$

where  $A$  is the basin area (km<sup>2</sup>),  $t$  the rainfall duration (h),  $\tau$  the time step, and  $P_n(\tau)$  the excess rainfall (mm/h) estimated by CN4GA. Within the WFIUH framework, hillslope flow velocity is estimated using empirical relationships based on local slope and land cover (Grimaldi et al., 2012), while channel flow velocity is automatically calibrated by the system so that the center of mass of WFIUH is equal to the basin lag time, that is estimated as 60% of basin concentration time (NRCS, 2008).

Compared to other empirical methods, EBA4SUB offers several advantages: it integrates physical and empirical approaches, requires limited input data, and adapts well to ungauged or poorly gauged basins. Unlike purely empirical formulas, it accounts for spatial terrain features and soil properties, improving the reliability of flood estimations in small catchments.

### **COSMO4SUB**

COSMO4SUB (Continuous Simulation Model for Small and Ungauged Basins) (Grimaldi et al., 2021, 2022) is a continuous rainfall-runoff model structured around three core modules: (1) rainfall simulation, (2) excess rainfall estimation, and (3) transformation of excess rainfall into runoff. While based on the same conceptual framework as EBA4SUB, its key advantage lies in operating as a continuous model, allowing for a more

objective and automated hydrological simulation process. Unlike event-based models, COSMO4SUB does not require the user to subjectively select critical inputs such as a critical rainfall duration, a predefined rainfall hyetograph shape, or antecedent moisture conditions. Instead, these are derived directly from continuous precipitation data, reducing user bias. The antecedent moisture condition (AMC), for example, is estimated dynamically using the cumulative rainfall over the five days prior to each event, allowing the model to adjust the Curve Number (CN) based on evolving soil moisture.

In the first module, rainfall time series can be generated using tools like STORAGE (STOchastic RAInfall Generation), a recently developed stochastic rainfall generator (De Luca et al., 2020; De Luca and Petroselli, 2021). STORAGE produces long, high-resolution synthetic rainfall series based on the observed data from rain-gauging stations and is applicable under both stationary and changing climate conditions. It is a modified version of the Neyman–Scott Rectangular Pulses (NSRP) model, featuring two key innovations. First, parameter estimation leverages multiple data series—including annual maximum rainfall, cumulative rainfall at annual and monthly scales, and the annual count of wet days—allowing calibration with datasets often longer than typical high-resolution records. Second, seasonality is captured through goniometric functions, making STORAGE more parsimonious than standard NSRP models, which require separate parameter sets for each month or season. In this study, the stationary version of STORAGE was employed to generate three synthetic rainfall time series, each 500 years long with a 15-minute resolution. Each series corresponds to one of the three case studies and was derived from the observed data of the respective rain gauge records.

In the second module, COSMO4SUB employs a continuous version of the CN4GA method, enhanced with a storm separation parameter ( $T_s$ ) to determine when initial abstraction resets between rainfall events. This further increases the accuracy of runoff estimation under changing rainfall patterns.

Finally, in the third module, the transformation of excess rainfall into runoff is handled via the Width Function-based Instantaneous Unit Hydrograph (WFIUH), as in EBA4SUB.

By enabling long-term simulations, COSMO4SUB allows for robust estimation of annual maximum discharges and the derivation of peak discharge–return period relationships, offering a more comprehensive and automated approach compared to traditional event-based models.

### *Handling Parameter Uncertainty in Hydrological Methods for Ungauged Basins*

When applying the investigated methodologies, the user must evaluate the input parameters required in different formulas. This task becomes particularly challenging for ungauged watersheds, where the absence of observed runoff data prevents calibration of more advanced models—many of which require a large number of input parameters. Under these circumstances, practitioners are often compelled to choose simpler approaches, such as the rational method or empirical formulas like Fuller’s formula. While these methods are less precise, they can be applied more easily.

For example, in the rational formula, the runoff coefficient  $C$  must be estimated. However, this is not straightforward: the reference tables (ASCE-WPCF 1969; Young et al. 2009; Dhakal et al. 2012) were not derived from basin-specific calibration but from expert consultation. In addition, land use and soil type classifications are coarse, with each category assigned a range of  $C$  values (e.g., for “residential suburban” areas,  $C$  ranges from 0.25 to 0.40). This variability introduces significant subjectivity, as the selection of a specific  $C$  value cannot be directly linked to a clear physical or conceptual basis (Grimaldi

& Petroselli, 2014). To illustrate the impact of this uncertainty, we present peak discharges computed using  $C$  values from 0.20 to 0.50.

Empirical formulas such as Fuller's differ from the rational method in that they are typically based on prior statistical relationships between observed rainfall and runoff in gauged basins. Parameters from these calibrations are then transferred to similar ungauged watersheds. In this study, we adopt parameter values for Fuller's formula reported by Salajegheh and Dastorani (2006), who compiled results from several Iranian basins using both their own and earlier local studies. While the watersheds analyzed here may differ in characteristics from those in the original calibration, this reflects a common challenge faced by hydrologists working in ungauged contexts: applying parameters developed for other regions when local calibration is not possible.

To address some of these limitations, conceptual event-based rainfall–runoff models tailored for ungauged basins—such as EBA4SUB—can be advantageous. One of EBA4SUB's strengths is its autocalibration of many parameters (e.g., WFIUH shape from concentration time, soil infiltration parameters, and Curve Number estimation from land cover). This reduces subjectivity compared to the rational and Fuller methods. Nevertheless, certain parameters still require user judgment, such as the choice of design rainfall distribution (e.g., Chicago hyetograph or rectangular hyetograph) and antecedent moisture conditions (AMC-II for average soil moisture or AMC-III for wet soils). We therefore provide peak discharges for both hyetograph types and AMC scenarios.

Despite these improvements, EBA4SUB still carries uncertainties stemming from user assumptions. Using a continuous rainfall–runoff model such as COSMO4SUB, coupled with a synthetic rainfall generator like STORAGE, can further reduce these uncertainties. Continuous simulation removes the need to preselect rainfall duration, design hyetograph, or AMC condition, while retaining the accuracy of a detailed model like EBA4SUB.

In the next chapter, we present the results in terms of peak discharge for the investigated case studies and selected methodologies. We recognize that these results are strongly influenced by the assumptions embedded within each method, particularly regarding parameter selection. Since the adopted parameters are inherently subjective and not derived from local calibration, the reported values should be interpreted with caution. Nevertheless, such constraints are a common and unavoidable feature of hydrological analyses in ungauged basins, where the absence of site-specific data necessitates reliance on generalized or transferred parameter values.

## Results

Table 1 summarizes the key characteristics of the investigated case studies, including contributing area, concentration time, Curve Numbers (CN) under AMC-II and AMC-III conditions (derived from the original NRCS formulation linking CN tables to land use and soil type), and the minimum and maximum runoff coefficients used in the rational formula.

As shown, all case studies exhibit relatively short concentration times (3.2–7.4 hours) and low AMC-II CN values (61.9–64.2), which are typical of natural, non-urbanized watersheds.

Table 1. Basic properties of the investigated case studies

	AREA (KM <sup>2</sup> )	TC (H)	CN-II (-)	CN-III (-)	CMIN (-)	CMAX (-)
Haffa	60.2	3.2	61.9	78.8	0.3	0.5
Al-Sinn	87.0	4.7	62.6	79.2	0.3	0.5
Abrash	182.4	7.4	64.2	80.1	0.3	0.5

Table 2 reports the rainfall analysis for the gauges located in the study areas, including DDF parameters, cumulative rainfall depths, and average intensities (as required for the rational formula application) for return periods of 5, 10, 50, 100, and 200 years.

Rainfall characteristics vary notably among the sites. In Haffa, cumulative depths range from 43.4 mm to 89.8 mm, with intensities between 13.6 mm/h and 28.1 mm/h, indicating relatively intense events over short durations. Al-Sinn exhibits lower intensities (9.5–13.0 mm/h) and narrower depth variation (44.8–61.0 mm), reflecting milder storm peaks. Abrash shows the highest cumulative depths (54.7–93.3 mm) and intermediate intensities (11.6–19.9 mm/h), suggesting longer-duration events with substantial total rainfall but less extreme peak rates compared to Haffa.

Table 2. DDF parameters and cumulative rainfall characteristics

DDF PARAMETERS TR (YEARS)	HAFFA				AL-SINN				ABRASH			
	A (MM/H)	N (-)	P (MM)	I (MM/H)	A (MM/H)	N (-)	P (MM)	I (MM/H)	A (MM/H)	N (-)	P (MM)	I (MM/H)
5	27.6	0.39	43.4	13.6	20.3	0.51	44.8	9.5	22.7	0.44	54.7	11.6
10	33.2	0.39	52.3	16.3	21.6	0.51	47.6	10.1	25.8	0.44	62.3	13.3
50	46.0	0.39	72.4	22.6	24.8	0.51	54.6	11.6	32.8	0.44	79.1	16.8
100	51.5	0.39	81.1	25.3	26.2	0.51	57.8	12.3	35.7	0.44	86.2	18.3
200	57.1	0.39	89.8	28.1	27.7	0.51	61.0	13.0	38.7	0.44	93.3	19.9

Table 3 presents the coefficients used in the application of Fuller’s formula, based on data reported by Salajegheh and Dastorani (2006). In particular, the B coefficient increases with return period, reflecting the expected growth of extreme flood events. For instance, in all three basins, B increases from 0.8 for a 5-year return period to 2.0 for a 100-year return period, and remains constant at 2.0 for the 100 and 200-year return period. This progression aligns with the empirical structure of Fuller’s formula. CF is constant across all basins and return periods, with a value of 0.116, indicating a uniform adjustment applied regardless of basin or flood frequency.  $Q_{ave}$  remains unchanged across return periods but varies by basin: 3.1 m<sup>3</sup>/s for Haffa, 4.1 m<sup>3</sup>/s for Al-Sinn, and 7.5 m<sup>3</sup>/s for Abrash. These values reflect the baseline flow characteristics of each watershed, with Abrash exhibiting the highest average flow. In contrast,  $Q_{max}$  increases significantly with return period, illustrating how flood risk escalates for rarer events. For example: In the Abrash basin,  $Q_{max}$  increases from 11.7 m<sup>3</sup>/s (5-year) to 42.4 m<sup>3</sup>/s (200-year); in Al-Sinn,  $Q_{max}$  rises from 6.5 m<sup>3</sup>/s to 23.5 m<sup>3</sup>/s over the same return periods; in Haffa,  $Q_{max}$  grows from 4.8 m<sup>3</sup>/s to 17.5 m<sup>3</sup>/s. These values demonstrate that although the average discharge is constant, the estimated peak discharge under extreme conditions varies considerably, both with return period and between basins. Abrash, in particular, shows the highest flood potential, consistent with its larger  $Q_{ave}$  and steeper increases in  $Q_{max}$ .

While the parameters of Fuller’s formula provide a useful reference and allow for quick and straightforward estimation of design discharge, they should be applied with caution, as

they are empirically derived and inherently linked to the specific hydrological, geological, and climatic conditions of the original study area. Applying them to different basins without proper calibration or validation may lead to inaccuracies, given the potential variability in watershed characteristics such as topography, land use, soil type, and rainfall patterns.

It is also important to note that the B values reported in Table 3 represent averages calculated from 10 homogeneous case studies conducted within the region investigated by Salajegheh and Dastorani (2006). For instance, for a 5-year return period, B values ranged from 0.62 to 0.97, with an average of 0.8 (as shown in Table 3). For a 200-year return period, they ranged from 1.00 to 2.99, with an average value of 2.0 (as shown in Table 3).

Similarly, the CF values in Table 3 are also averages derived from the same set of 10 case studies. However, unlike the B values, the CF values are independent of the return period. According to Salajegheh and Dastorani (2006), CF values ranged from 0.035 to 0.45, with an average of 0.116 (as shown in Table 3).

Table 3. Fuller’s formula input parameters

TR (YEARS)	HAFFA				AL-SINN				ABRASH			
	B (-)	CF (-)	QAVE (M <sup>3</sup> /S)	QMAX (M <sup>3</sup> /S)	B (-)	CF (-)	QAVE (M <sup>3</sup> /S)	QMAX (M <sup>3</sup> /S)	B (-)	CF (-)	QAVE (M <sup>3</sup> /S)	QMAX (M <sup>3</sup> /S)
5	0.8	0.116	3.1	4.8	0.8	0.116	4.1	6.5	0.8	0.116	7.5	11.7
10	1.3	0.116	3.1	7.1	1.3	0.116	4.1	9.5	1.3	0.116	7.5	17.2
50	1.8	0.116	3.1	12.7	1.8	0.116	4.1	17.1	1.8	0.116	7.5	30.9
100	2.0	0.116	3.1	15.4	2.0	0.116	4.1	20.6	2.0	0.116	7.5	37.3
200	2.0	0.116	3.1	17.5	2.0	0.116	4.1	23.5	2.0	0.116	7.5	42.4

Table 4 presents the peak discharges estimated for the Haffa, Al-Sinn, and Abrash case studies using multiple methodologies and for different return periods. The results confirm a substantial variability between approaches, which becomes particularly pronounced at higher return periods. For example, in Haffa, for a 200-year return period, estimates range from 73.9 m<sup>3</sup>/s using Fuller’s formula to 309.8 m<sup>3</sup>/s with EBA4SUB employing the Chicago hyetograph under AMC-III conditions—a difference of more than fourfold. Comparable spreads occur in Al-Sinn (91.0–274.0 m<sup>3</sup>/s) and Abrash (133.1–472.2 m<sup>3</sup>/s), reflecting the sensitivity of peak discharge predictions to methodological choices.

Fuller’s formula frequently produces the lowest estimates at higher return periods, but its output is highly dependent on the selected coefficients. Without calibration to the specific hydrological characteristics of the basin, the results may be severely underestimated—or, less frequently, overestimated—limiting its reliability for design purposes. The rational method consistently produces higher values than Fuller’s formula, even when adopting the minimum runoff coefficient (Rat.Cmin), highlighting its more conservative nature.

EBA4SUB results are strongly influenced by both the assumed hyetograph and antecedent moisture conditions (AMC). For identical AMC conditions, the Chicago hyetograph (EBA-C) generally produces higher peaks than the rectangular hyetograph (EBA-R). For instance, in Haffa at the 200-year return period under AMC-III, EBA-C yields 309.8 m<sup>3</sup>/s compared to 235.7 m<sup>3</sup>/s for EBA-R. Across all case studies, AMC-III scenarios produce larger discharges than AMC-II, reflecting the heightened runoff potential of saturated soils.

The COSMO4SUB continuous modelling approach produces high peak discharges, although not always the highest—e.g., in Haffa at 200 years, its estimate is below that of EBA-C-III. However, COSMO4SUB has the advantage of being the least subjective

method in the comparison, as it avoids event-based assumptions such as fixed runoff coefficients or predetermined hyetograph shapes.

The comparison of peak discharge estimates for the Haffa, Al-Sinn, and Abrash basins across multiple return periods highlights significant differences between the hydrological methods considered. Across all return periods and basins, Fuller's formula consistently produces the lowest discharge values. For example, in the Haffa basin, Fuller estimates increase from 20.4 m<sup>3</sup>/s for a 5-year return period to 73.9 m<sup>3</sup>/s for the 200-year event. In contrast, the COSMO4SUB model yields much higher estimates, ranging from 162.4 to 287.5 m<sup>3</sup>/s over the same return periods. Similar patterns are evident in the other two basins: in Al-Sinn, COSMO4SUB outputs range from 118.0 to 274.0 m<sup>3</sup>/s, while Fuller estimates remain significantly lower, from 25.1 to 91.0 m<sup>3</sup>/s. The Abrash basin shows Fuller values between 38.5 and 139.3 m<sup>3</sup>/s, while COSMO4SUB estimates range from 267.4 to 472.2 m<sup>3</sup>/s.

A statistical analysis reinforces these discrepancies. When averaged across all return periods, Fuller's method yields mean peak discharges of approximately 48.6 m<sup>3</sup>/s for Haffa, 59.8 m<sup>3</sup>/s for Al-Sinn, and 91.6 m<sup>3</sup>/s for Abrash. In contrast, the COSMO4SUB model produces much higher averages: 229.4 m<sup>3</sup>/s, 202.0 m<sup>3</sup>/s, and 365.0 m<sup>3</sup>/s, respectively. The standard deviation of COSMO4SUB estimates is also considerably larger, indicating a greater sensitivity to increasing return periods and perhaps a more realistic reflection of hydrological extremes. For instance, in the Abrash basin, the standard deviation for Fuller is about 37.5 m<sup>3</sup>/s, while for COSMO it is nearly double, at 71.8 m<sup>3</sup>/s.

To better understand the extent of underestimation, the relative difference between Fuller and COSMO4SUB estimates was calculated. Results show that Fuller underestimates  $Q_p$  by 65% to nearly 87%, depending on the basin and return period. The largest discrepancies occur at lower return periods. For example, in Haffa and Abrash, the 5-year  $Q_p$  estimated by Fuller is around 87% lower than COSMO4SUB's estimate, while the difference narrows slightly to around 74–70% for the 200-year event. Even in Al-Sinn, which has somewhat less pronounced differences, Fuller's underestimation remains above 66% across return periods.

These findings confirm that empirical methods like Fuller's formula and the Rational Method, especially when using conservative (i.e., minimum) runoff coefficients, tend to significantly underestimate peak discharges when compared to more detailed physically based or calibrated approaches.

Table 4. Peak discharges for the investigated case studies obtained using different methodologies: Fuller’s formula; rational method with minimum runoff coefficient (Rat.Cmin) and maximum runoff coefficient (Rat.Cmax); EBA4SUB with rectangular hyetograph (EBA-R) or Chicago hyetograph (EBA-C) under AMC-II and AMC-III conditions; and continuous modelling with STORAGE + COSMO4SUB (COSMO).

HAFFA QP (M <sup>3</sup> /S)								
TR (YEARS)	FULLER	RAT.CMIN	RAT.CMAX	EBA-R-II	EBA-R-III	EBA-C-II	EBA-C-III	COSMO
5	20.4	69.0	115.0	7.9	68.0	8.6	78.9	162.4
10	30.0	83.1	138.5	20.3	97.9	21.2	116.9	187.5
50	53.8	115.1	191.8	60.0	168.1	66.8	215.2	249.8
100	64.9	128.9	214.8	80.5	201.5	91.9	261.7	259.6
200	73.9	142.7	237.8	103.9	235.7	120.1	309.8	287.5
AL-SINN QP (M <sup>3</sup> /S)								
TR (YEARS)	FULLER	RAT.CMIN	RAT.CMAX	EBA-R-II	EBA-R-III	EBA-C-II	EBA-C-III	COSMO
5	25.1	68.9	114.9	9.3	65.2	10.1	78.1	118.0
10	36.9	73.3	122.1	15.5	79.8	17.0	95.5	143.7
50	66.2	84.1	140.1	33.9	113.8	37.3	135.3	221.5
100	79.9	89.0	148.3	43.1	129.1	47.1	153.2	252.8
200	91.0	93.9	156.5	53.1	145.3	59.0	172.6	274.0
ABRASH QP (M <sup>3</sup> /S)								
TR (YEARS)	FULLER	RAT.CMIN	RAT.CMAX	EBA-R-II	EBA-R-III	EBA-C-II	EBA-C-III	COSMO
5	38.5	112.7	187.8	31.4	112.7	41.3	159.3	267.4
10	56.5	128.4	214.0	44.8	148.4	63.8	204.4	311.6
50	101.4	163.0	271.7	86.1	231.6	128.1	306.1	370.2
100	122.3	177.7	296.1	107.9	269.3	161.2	349.6	403.8
200	139.3	192.3	320.4	133.1	307.1	196.6	393.3	472.2

### Discussion

The results obtained in this study align with findings reported in the existing literature, yet they also highlight important nuances regarding the applicability and limitations of various hydrological modeling approaches. For instance, Petroselli et al. (2019) observed that peak discharge estimates generated by the continuous COSMO4SUB model were lower than those from the event-based EBA4SUB approach under Antecedent Moisture Condition III (AMC-III), but exceeded EBA4SUB outputs under AMC-II conditions. This underscores the critical role that antecedent moisture conditions play in shaping flood hydrographs, as well as the inherent subjectivity and sensitivity of event-based methods to such parameters. While event-based approaches like EBA4SUB can reduce some uncertainty in hydrograph design compared to simpler empirical models, they still depend heavily on assumptions about rainfall duration, temporal distribution, and AMC classification—factors that can substantially influence outcomes and limit their transferability across different contexts.

Similarly, Grimaldi et al. (2012a) found that continuous modeling techniques tend to produce higher peak discharge estimates than event-based methods under AMC-II conditions, with differences reaching 20% to 40% for a 100-year return period. Winter et al. (2019) further supported these findings, showing that continuous models better capture the temporal variability of rainfall, soil moisture dynamics, and catchment response, leading to generally more conservative and arguably more realistic flood predictions. However, it is important to recognize that these studies were conducted primarily in

Mediterranean and temperate environments, where relatively dense hydrometeorological monitoring and detailed basin characterization support the calibration and validation of complex continuous models.

In contrast, many developing regions, including the case studies examined here, face significant data scarcity and heightened variability in climatic and soil conditions. This limits the applicability and robustness of both empirical and event-based methods, which are often still preferred for their simplicity and minimal data requirements. Simple approaches such as the Rational Method or Fuller formula, although widely used in ungauged or poorly gauged basins, frequently fail to provide reliable estimates because they do not adequately account for local factors like soil heterogeneity, slope, and land use, all of which strongly influence runoff dynamics.

A preliminary comparison between the COSMO4SUB-derived peak discharges and published estimates from hydrologically similar catchments in northern Lebanon and southern Turkey indicates that the model outputs are of a consistent order of magnitude. Regional studies and flood-frequency analyses in small- to medium-sized Mediterranean basins report 100-year specific peak discharges generally below about  $2 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ , though values vary widely depending on rainfall regime and basin steepness (Aydoğan et al., 2016; AlZaatiti et al., 2025). For instance, Aydoğan et al. (2016) analyzed regional flood frequencies in the Çoruh Basin of northeastern Turkey, while AlZaatiti et al. (2025) simulated flood responses in the Abou Ali Basin of northern Lebanon, both reporting event magnitudes consistent with the lower range of COSMO4SUB estimates. The specific peak discharges derived from COSMO4SUB ( $\approx 2.6\text{--}4.8 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$  for the 200-year event) therefore lie toward the upper end of the expected regional range, reflecting the relatively short concentration times and steep slopes of the studied watersheds. This scaling behavior is also consistent with the sub-linear relationship between peak flow and drainage area reported by Ogden and Dawdy (2003), who showed that smaller, steeper Hortonian catchments exhibit higher unit discharges. Although these regional comparisons rely on hydrological similarity rather than direct gauged observations, they provide additional confidence that COSMO4SUB yields physically plausible results for ungauged Mediterranean basins.

While continuous models like COSMO4SUB show great promise in improving flood estimation accuracy and resilience planning—especially by integrating continuous rainfall-runoff processes within a flexible event-based framework—they are not without challenges. These models require significant computational resources, skilled personnel, and at least some level of data for calibration, which may be limited in many developing country contexts. Furthermore, the performance of continuous models can be undermined by uncertainties in input data, such as sparse rainfall measurements and imprecise catchment characterization, which remain major obstacles. Another possible limitation of continuous modelling relates to the use of a stochastic rainfall generator. While these generators are useful for producing long synthetic rainfall series and exploring hydrological variability, they come with several limitations. A key assumption is that historical rainfall statistics—such as intensity, frequency, and temporal structure—are stationary and representative of future conditions, which may not hold under changing climate or land-use scenarios. Additionally, many stochastic models simplify rainfall processes, potentially overlooking extreme events, multi-day dependencies, or spatial correlations across catchments. These simplifications can introduce uncertainty into derived hydrological outputs, especially in design applications such as flood estimation. Therefore, while stochastic rainfall generators offer valuable insights, their results should be interpreted with caution and, where possible, supported by calibration against observed events or complemented with physically based approaches.

Moving forward, addressing these limitations requires a multipronged approach. First, expanding hydrometeorological monitoring networks and improving data quality through remote sensing and crowdsourced observations can enhance model inputs. Indeed, recent advances in remote-sensing-based approaches further support the need for data-efficient hydrological tools in ungauged regions. For example, Mao et al. (2025) demonstrated that variations in relative surface water extent derived from satellite imagery can reliably capture river discharge dynamics. Their findings highlight how remote-sensing methodologies can complement continuous modeling frameworks like COSMO4SUB by providing discharge proxies in data-scarce areas, thereby improving regional flood estimation and water resources assessment. Second, developing hybrid methods that combine the simplicity of empirical models with the process-based rigor of continuous simulations could offer more practical solutions in data-poor regions. Third, further research into uncertainty quantification and sensitivity analysis is needed to better understand how input variability propagates through different modeling frameworks. Lastly, strengthening local capacity for model calibration and validation, possibly through regional cooperation and knowledge sharing, is essential to adapt these tools effectively to diverse hydrological settings.

In summary, while event-based and empirical methods remain useful due to their simplicity and lower data demands, continuous modeling offers advantages in capturing catchment dynamics more realistically. However, its successful application depends on the availability of sufficient data and appropriate calibration. Given the challenges in many developing regions, a balanced approach that considers the strengths and limitations of each method is advisable. Future efforts should focus on improving data collection, exploring hybrid modeling techniques, and enhancing local expertise to better adapt these tools to varying hydrological conditions.

## Conclusions

This study evaluated multiple approaches for estimating peak discharges in small, ungauged basins in Syria, including empirical/conceptual methods (Fuller's formula, Rational Method), event-based models (EBA4SUB), and continuous modeling (COSMO4SUB). Results revealed substantial variability among methods, particularly for high-return-period events. Empirical formulas often underestimated peak discharges and were highly sensitive to coefficient selection, while event-based approaches, although more flexible, remain influenced by assumptions on hyetograph shape and antecedent moisture conditions.

The COSMO4SUB continuous modeling approach demonstrated clear advantages. It produces high peak discharge estimates (favoring safety) without relying heavily on subjective assumptions, better representing catchment processes such as soil saturation, runoff generation, and rainfall variability. This makes it particularly suitable for developing countries, where monitoring infrastructure is limited and ungauged basins are common, offering a robust and practical tool for flood estimation and resilience planning. Continuous modeling, exemplified by COSMO4SUB, provides indeed a reliable, assumption-light alternative to traditional empirical and event-based methods, enhancing the accuracy and robustness of flood risk assessment in developing countries with small, ungauged catchments.

Anyway, continuous modeling still requires catchment data for calibration, which may be limited in some regions, and this study considered only three case studies. Future work should extend these comparisons across diverse basins, explore hybrid empirical-process-based approaches, and integrate emerging data sources (e.g., remote sensing or machine learning approaches) to improve flood estimation in data-scarce environments.

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