Automated GIS-Based Hydrological Modeling Framework for Flood Hydrograph Estimation in Ungauged Mediterranean Catchments: A Case Study of Sicily

Dott. Biagio Saya[a,*]

[a]*Independent Researcher, Messina, Italy*

Abstract

The estimation of design flood hydrographs in ungauged Mediterranean catchments remains a persistent challenge for hydrological engineering, flood hazard assessment, and territorial risk planning. The absence of discharge observations, coupled with the high temporal concentration of precipitation and the marked geomorphological variability of small basins, renders conventional calibration-based approaches only partially applicable. Within this context, the present study proposes a fully automated GIS-based framework, implemented in Python and integrated into the QGIS environment via the PyQGIS API, for the derivation of flood hydrographs in Sicilian basins.

The framework couples regional rainfall frequency analysis, distributed SCS-CN runoff abstraction, and time-area routing into a single computational chain. The procedure is designed to process multiple catchments simultaneously, significantly reducing operator dependence while ensuring strict methodological reproducibility. Three hydrological formulations are compared: the Rational Method, a synthetic Chicago-type hyetograph, and a kinematic time-area convolution scheme. The resulting workflow is highly suited to flash-flood-prone Mediterranean watersheds, where a rapid hydrological response, limited data availability, and the need for consistent regional design criteria demand a robust and scalable modeling approach.

Keywords: PyQGIS, hydrological automation, flood hydrograph, ungauged basin, SCS-CN, time-area method, Mediterranean catchments, Sicily

---

1. Introduction

Flooding constitutes one of the most severe natural hazards affecting the Mediterranean basin, with particularly acute consequences in small and steep catchments exposed to short-duration convective rainfall events. In such environments, the hydrological response is typically rapid, highly non-linear, and heavily conditioned by basin morphology, land cover, soil properties, and rainfall temporal structure [1, 2]. These characteristics are exceptionally relevant in Sicily, where hydrological hazard is amplified by irregular precipitation regimes, orographic effects, and the recurrent occurrence of intense storm systems.

---

[*] Corresponding author

Email address: `biagiosaya@gmail.com` `ORCID: https://orcid.org/0000-0001-8977-996X` (Dott. Biagio Saya)

This scientific and operational challenge is exacerbated in ungauged basins, where the absence of streamflow records precludes the direct calibration and validation of conventional rainfall-runoff models. In these contexts, design flood estimation must rely on regionalized climatic information, physically interpretable surrogate parameters, and a basin-scale spatial representation of runoff generation and routing processes [3, 4, 5]. This issue extends beyond theoretical hydrology; it bears direct implications for flood hazard mapping, hydraulic design, land-use planning, and climate adaptation policies.

Regional studies in Sicily have demonstrated that extreme rainfall can be robustly characterized through regional frequency analysis, allowing the derivation of design precipitation that is consistent across climatically homogeneous zones [6, 7]. Simultaneously, institutional reports emphasize that climate variability and non-stationary trends in precipitation demand updated hydrological frameworks rather than relying on static historical assumptions [8]. Therefore, the design of flood hydrographs in this setting requires a methodology that is regionally coherent, spatially explicit, and operationally reproducible.

To address this gap, this paper proposes an open-source hydrological framework embedded within QGIS utilizing PyQGIS. The framework unifies rainfall regionalization, runoff abstraction, and hydrograph routing within a cohesive workflow designed for application across multiple Sicilian catchments. Its core contribution lies not merely in the application of established hydrological formulas, but in the formalization of an end-to-end computational structure that seamlessly translates GIS inputs into hydrologically meaningful outputs with minimal manual intervention. In this respect, the approach strongly aligns with broader advancements in open-source flood modeling and GIS-based hydrological automation [9, 10, 11, 12].

1.1. Research background

The literature on ungauged basin hydrology has long recognized the necessity of combining indirect regional information with simplified, yet physically defensible, rainfall-runoff formulations. Methods based on geomorphology, regional frequency analysis, and empirical runoff abstraction have been utilized for decades. However, their practical application often remains hindered when model components are fragmented across disparate tools or procedures. Recent contributions increasingly advocate for integrated workflows, particularly in open-source environments, where geospatial preprocessing, hydrological computation, and cartographic visualization can be orchestrated within a unified platform [14, 3, 13].

1.2. Aim of the study

The primary aim of this study is to develop and present a comprehensive, reproducible GIS-based framework for flood hydrograph estimation in ungauged Mediterranean catchments. The framework is engineered to: (i) derive design rainfall from regionalized frequency information; (ii) estimate effective rainfall using a distributed SCS-CN abstraction method; (iii) generate flood hydrographs via time-area routing; and (iv) automate the entire workflow to facilitate batch processing across multiple basins. The ultimate output is a robust methodology tailored for both advanced scientific analysis and practical flood risk assessment.

2. Hydrological and Territorial Context

Sicily serves as a highly suitable case study for hydrological automation, as it exhibits marked climatic variability, steep topographical relief, heterogeneous land use, and a dense, albeit unevenly distributed, hydrographic network. Small and medium-sized basins in the region typically respond to precipitation with short lag times and pronounced flood peaks. This makes them exceedingly vulnerable to urban encroachment, land degradation, and increasing rainfall intensity. Consequently, any basin-scale hydrological framework must accurately capture terrain controls and rainfall concentration dynamics.

Furthermore, Sicily benefits from an established body of literature regarding extreme precipitation, regional rainfall modeling, and flood risk analysis. This solid scientific background provides a reliable basis for regionalization, enabling the proposed framework to be anchored in validated hydrological knowledge rather than relying on ad hoc assumptions [6, 7, 14]. Consistency across basins is vital in ungauged basin analysis, as it permits comparative evaluations under uniform methodological premises.

2.1. Need for reproducible workflows

A recurring limitation in applied hydrology is the reliance on manual, case-specific procedures that are challenging to reproduce or scale. GIS-based automation effectively resolves this limitation by allowing modelers to formalize data acquisition, layer processing, parameter extraction, and result generation within a single computational environment. Open-source GIS tools have already proven their efficacy in floodplain delineation, runoff estimation, and hydrodynamic pre-processing [9, 10, 11]. This study systematically extends this paradigm to the estimation of design flood hydrographs in ungauged basins.

3. Theoretical Framework and Mathematical Formulations

3.1. Regional rainfall frequency analysis

The initial step in the proposed framework involves estimating design rainfall through regional frequency analysis. In Sicily, regionalized Depth-Duration-Frequency (DDF) curves provide a robust foundation for translating return period information into rainfall depths for various durations [6]. The general DDF relationship is expressed as:

$$P_{gross}(t, Tr) = h_r(Tr) \cdot a_{24} \cdot \left(\frac{t}{24}\right)^n \tag{1}$$

where $P_{gross}(t, Tr)$ is the gross rainfall depth, $h_r(Tr)$ is the regional growth factor, a_{24} is the expected rainfall depth for a 24-hour reference event, and n is the regional scaling exponent.

This step is critical because design rainfall values strictly dictate the forcing condition of the entire hydrological model. In ungauged environments, the reliability of discharge estimates is intrinsically linked to the credibility of the adopted rainfall regionalization [6, 7].

3.2. Temporal structure of design rainfall

Total rainfall depth must be distributed over time to generate an appropriate design hyetograph. Temporal disaggregation is a primary controlling factor of the basin's peak response. Two storm events yielding identical total depths may generate vastly different hydrographs depending on their temporal concentration. This phenomenon is particularly critical in steep Mediterranean catchments, where the synchronization between peak rainfall intensity and basin time of concentration can trigger rapid flash floods.

To accommodate this, the framework supports alternative storm structures, including a Chicago-style hyetograph and a kinematic alternating block hyetograph. Treating the hyetograph selection as a scenario variable allows for a transparent exploration of hydrograph sensitivity to rainfall timing [18].

3.3. Distributed rainfall excess estimation

The transformation of gross rainfall into effective rainfall is executed using the Soil Conservation Service Curve Number (SCS-CN) method, applied distributively across the basin surface. The SCS-CN method remains standard practice for estimating direct runoff in ungauged basins due to its reliance on readily available data while maintaining an interpretable link between land cover, soil properties, and runoff potential [15, 16, 17, 20].

The potential maximum retention S (in mm) is defined as:

$$S = \frac{25400}{CN} - 254 \tag{2}$$

and the initial abstraction I_a is estimated as:

$$I_a = 0.2 \cdot S \tag{3}$$

The net rainfall is subsequently computed as:

$$P_{net}(t) = \begin{cases} 0 & \text{if } P_{gross}(t) \leq I_a \\ \frac{[P_{gross}(t)-I_a]^2}{P_{gross}(t)-I_a+S} & \text{if } P_{gross}(t) > I_a \end{cases} \tag{4}$$

Despite its empirical origins, the SCS-CN method offers a practical equilibrium between simplicity and hydrological plausibility. Embedded within a distributed GIS architecture, CN values are dynamically extracted from underlying soil and land-use rasters, allowing for spatially differentiated abstraction mapping [15, 20].

3.4. Time-area routing

The final transformation from rainfall excess to an outlet discharge hydrograph is achieved via a time-area convolution scheme. This methodology partitions the basin into isochronal zones based on travel time to the outlet. Runoff generated within each zone is routed according to the temporal distribution of the effective rainfall. Discharge Q at timestep m is expressed as:

$$Q[m] = 0.278 \sum_{j=1}^{N_p} i_{net}[j] \cdot A[m-j+1] \tag{5}$$

where $i_{net}[j]$ represents the effective rainfall intensity (mm/h) and $A[k]$ is the contributing area (km^2) within a specific travel time class.

The time-area approach is highly advantageous for steep, compact catchments as it accurately preserves the temporal structure of the basin's response. In comparison to the traditional Rational Method, it provides a superior representation of attenuation, travel-time dispersion, and spatial runoff aggregation [13, 19].

3.5. Conceptual integration of the model

The proposed methodology is structured as a sequential hydrological chain (Table 1). In ungauged basin hydrology, the coherent integration of these processes is frequently more critical than the theoretical complexity of individual formulas [3, 14].

Table 1: Main modeling blocks and their scientific role within the framework.

Modeling Block	**Geospatial/Numerical Input**	**Scientific Role**
Rainfall regionalization	Regional DDF curves, return period	Translates climate statistics into event rainfall depths.
SCS-CN abstraction	CN maps, land use, hydrologic soil groups	Estimates effective rainfall and losses on a distributed grid.
Time-area routing	Isochrones, basin geometry, travel times	Reconstructs hydrograph peak and temporal attenuation.
PyQGIS automation	GIS layers, batch processing scripts	Standardizes calculations and minimizes operator bias.

4. Algorithm Design and GIS Automation Architecture

The framework is scripted in Python utilizing the PyQGIS API, aimed at fully automating the hydrological workflow from raw geospatial input to final hydrograph export. From a scientific perspective, explicitly linking spatial datasets to hydrological variables guarantees analytical transparency and exact reproducibility.

4.1. Input data structure

The model ingests high-resolution Digital Elevation Models (DEM), drainage network layers, land-use shapefiles, soil thematic maps, and regional rainfall parameter grids. The DEM serves as the baseline for deriving slopes, flow direction matrices, and isochrones, while intersecting land-use and soil layers yields the Curve Number grid.

4.2. Computation sequence

The logic proceeds through the following computational steps:

1. Data ingestion and topological validation.
2. Raster and vector preprocessing (reprojection, clipping).
3. Basin segmentation and vector zonal statistics.
4. Design rainfall synthesis.
5. Temporal disaggregation of the design storm.
6. Spatially distributed effective rainfall estimation (SCS-CN).
7. Hydrograph routing via time-area convolution.
8. Tabular and cartographic export.

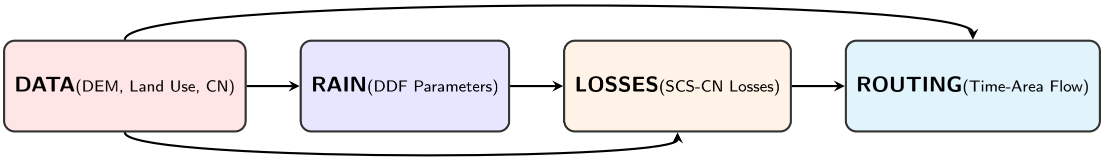


Figure 1: Modular pipeline architecture of the proposed automated PyQGIS framework.

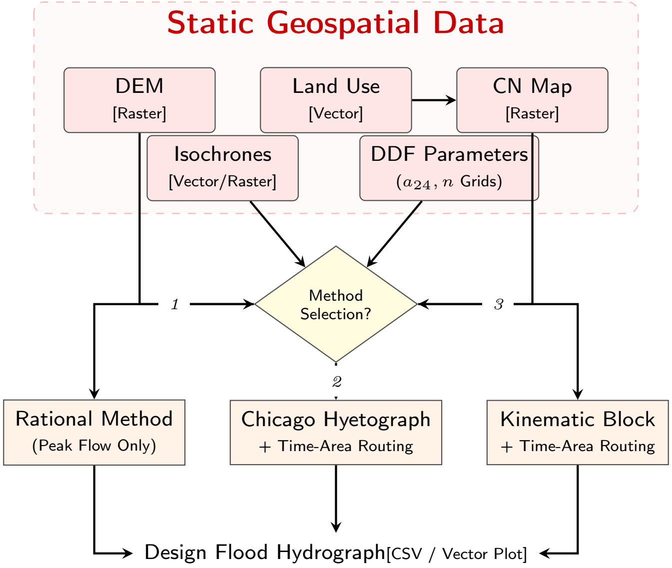


Figure 2: Detailed logical dataflow mapping inputs to the respective hydrological core routing methods.

4.3. Flowchart representation

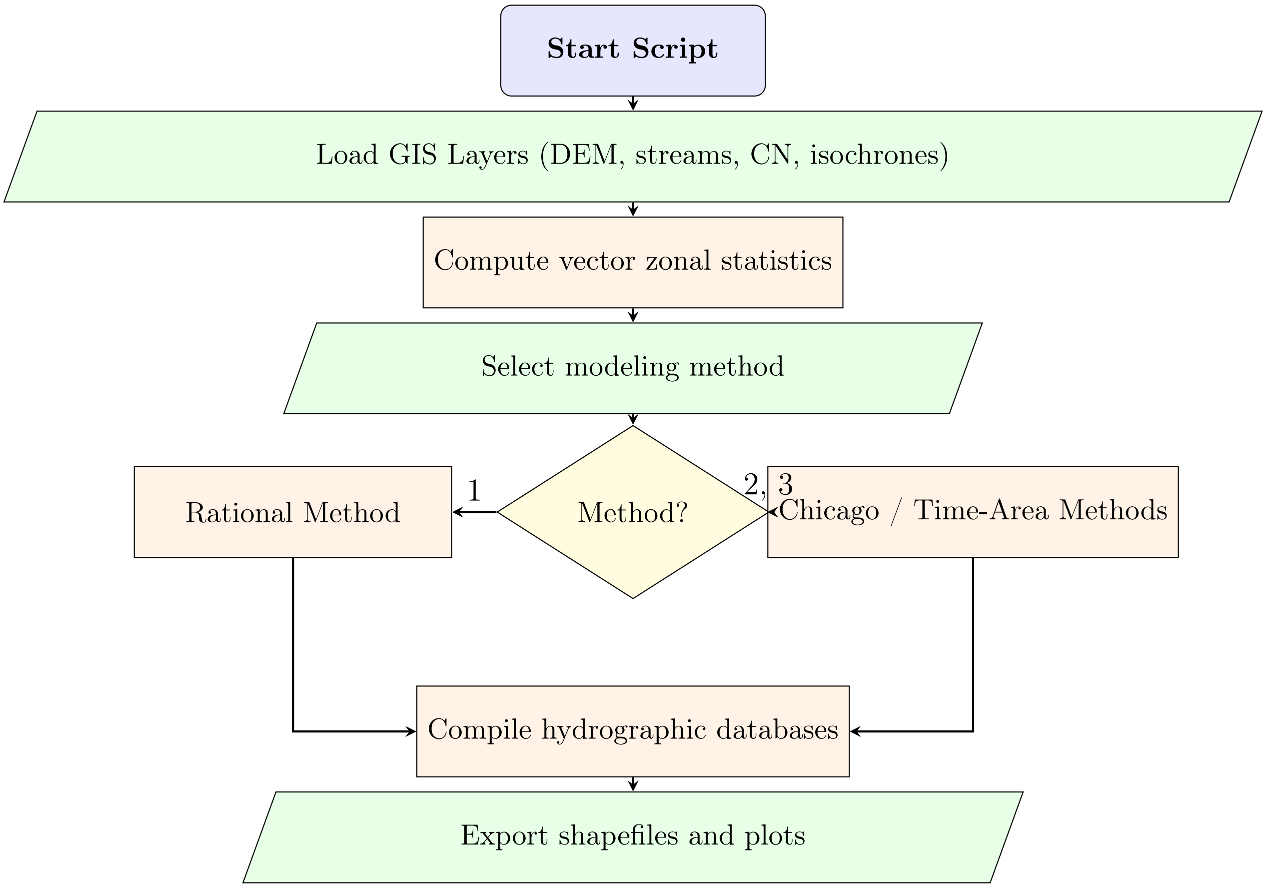


Figure 3: Algorithmic flowchart representing the PyQGIS automation processing sequence.

4.4. Scientific value of automation

Automation in this context acts as a methodological safeguard rather than a mere technical convenience. In traditional hydrological assessments, repetitive manual interventions frequently introduce inconsistencies in spatial aggregation or parameter scaling.

By contrast, a scripted workflow mathematically guarantees that every scenario adheres to identical rules, fulfilling the strict reproducibility requirements of ungauged basin studies.

5. Case Study Setup: Sicilian Hydrographic Basins

The proposed framework was validated on a subset of Sicilian hydrographic basins chosen to encapsulate diverse geomorphological and land-cover archetypes. Sicily presents a highly relevant testing ground due to its unique combination of mountainous headwaters, highly variable soil permeability, and intense rainfall patterns.

5.1. Morphometric characteristics

The targeted basins are generally small to medium in scale, featuring steep channel gradients, minimal floodplain storage, and extremely short time-of-concentration values. Such topography is notorious for yielding abrupt runoff peaks during convective storms. This geomorphological reality accentuates the necessity of the time-area method, as travel-time dispersion critically shapes the resulting hydrograph.

5.2. Geospatial database

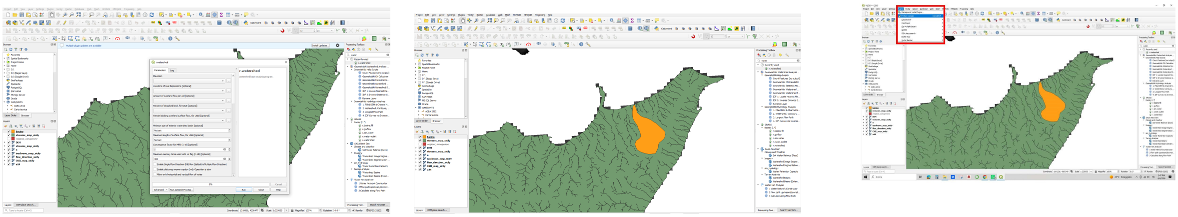
The baseline geospatial database incorporates a 10-meter resolution DEM, CN maps synthesized from standardized land-use and pedological databases, and continuous rainfall parameter grids. This integration of heterogeneous but standardized GIS layers aligns with best practices in open-source environmental modeling, ensuring the framework's transferability to broader Mediterranean contexts [9, 10, 11].

Table 2: Input datasets and corresponding model computational outputs.

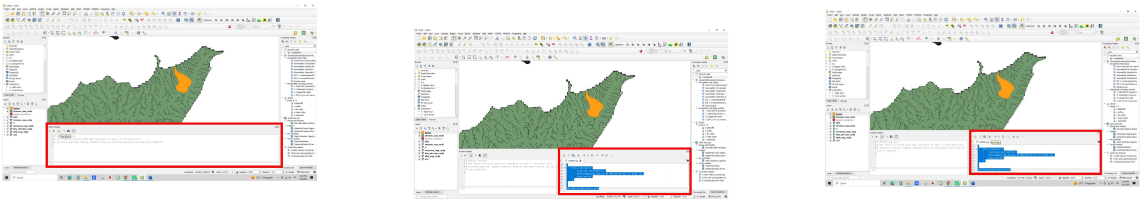
Input Layer	**Processing Step**	**Hydrological Output**
DEM	Terrain analysis, slope, routing	Basin morphology and isochrones
Land Use	Spatial intersection	Runoff potential by spatial unit
Soil Maps	Hydrologic soil grouping	Curve Number parameterization
DDF Grids	Frequency analysis	Synthetic design hyetographs
Isochrones	Convolution routing	Final outlet hydrograph

5.3. GIS-Based Watershed Delineation Workflow

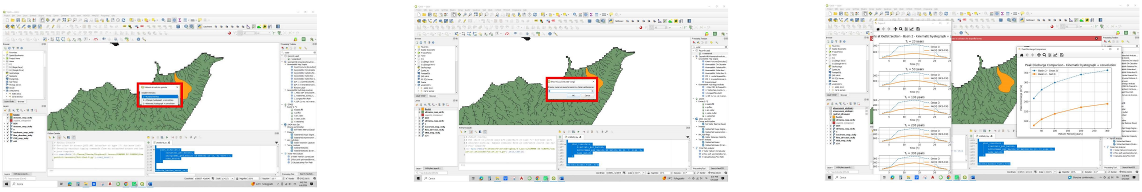
To accurately derive design floods within the integrated framework, strict topographical definition of the contributing watershed is mandatory. The sequential pipeline executed within QGIS to extract the target catchment is illustrated in Figure 4.



(a) DEM Loading (b) Depression Filling (c) Flow Direction



(d) Flow Accumulation (e) Stream Network (f) Outlet Selection



(g) Watershed Delineation (h) Polygon Vectorization (i) Plugin Integration

Figure 4: Step-by-step methodological workflow in QGIS for morphometric processing, watershed boundary delineation, and final geospatial integration into the PyQGIS model.

The extraction procedure strictly follows a digital terrain analysis paradigm structured into four sequential phases:

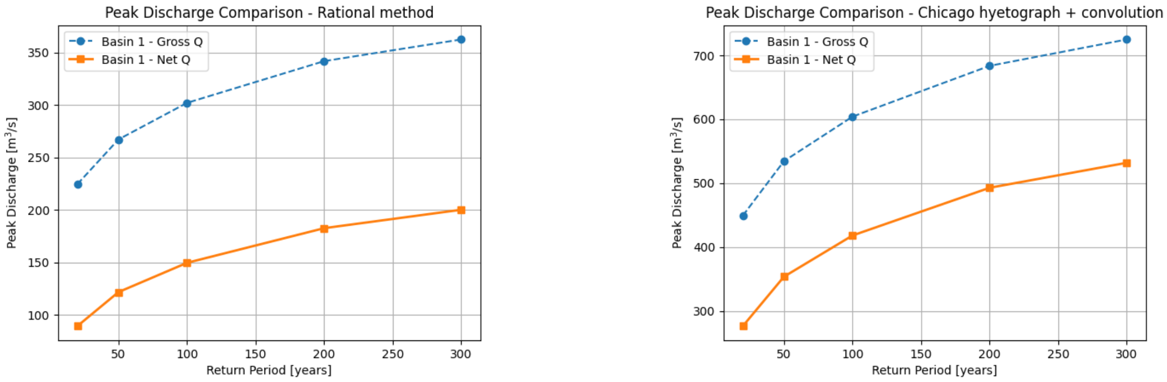
1. **Topographic Data Pre-processing:** Initial ingestion of the DEM (Figure 4a) followed by a sink-filling algorithm (*Fill Sinks*, Figure 4b) to eliminate computational anomalies and ensure continuous overland flow routing.
2. **Hydrographic Flow Analysis:** Downstream pathways are calculated to generate a cell-to-cell flow direction matrix (Figure 4c). Subsequently, the cumulative upslope area is quantified (Figure 4d) to map preferential drainage pathways.
3. **Catchment Boundary Delineation:** By implementing a flow accumulation threshold, the theoretical stream network is vectorized (Figure 4e). Once the target outlet section (*Pour Point*) is defined (Figure 4f), the algorithm isolates the precise contributing drainage area (Figure 4g).
4. **Vector Conversion and Plugin Deployment:** The raster watershed is ultimately converted into a vector format (Figure 4h), explicitly delineating the geographical domain for the plugin interface (Figure 4i) where land-use maps, soil classes, and CN values are overlaid.

6. Results and Discussion

The results are evaluated as a comparative analysis of hydrograph generation strategies. The principal objective is to ascertain how structural modeling assumptions govern the final estimation of peak discharge and hydrograph morphology.

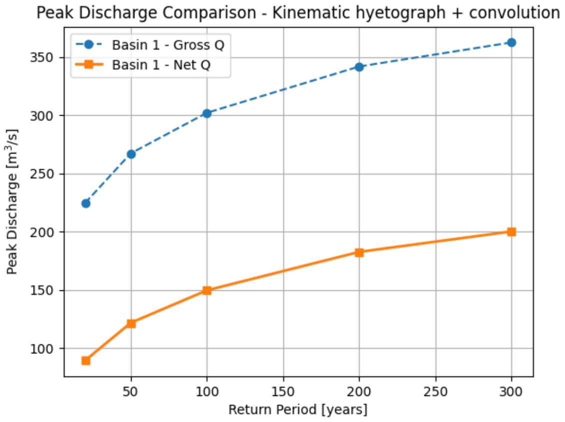
6.1. Peak discharge sensitivity analysis

Figures 5a, 5b, and 5c detail the variation in peak discharge Q_{peak} across escalating return periods.



(a) Rational Method.

(b) Chicago Hyetograph.



(c) Kinematic Alternating Block.

Figure 5: Multi-basin peak discharge scaling behaviors under differing return periods.

Lumped methods (e.g., Rational Method) consistently yield higher peaks as they compress spatial travel times and inherently neglect the internal attenuation generated by basin storage. Conversely, time-area methods distribute runoff production over time and space, yielding hydrographs that are physically consistent with the actual drainage network geometry [14, 1, 19].

Table 3: Interpretation of peak discharge behavior across different routing methods.

Modeling Observation	**Hydrological Interpretation**
Lumped methods yield higher peaks	They compress spatial travel times and ignore natural channel routing storage.
Time-area methods reduce peak magnitude	They dynamically represent hydrograph attenuation and kinematic routing delay.
Higher return periods increase nonlinearity	Soil storage thresholds saturate rapidly, transitioning to purely event-driven runoff.

6.2. Runoff hydrograph dynamics

Figures 6 and 7 present representative hydrographs computed for diverse design scenarios. The non-linearity between rainfall forcing and hydrograph output is strongly governed by the interplay between initial abstraction and routing delay. At high return periods, abstraction thresholds are aggressively exceeded, resulting in a sharply amplified hydrographic response typical of Mediterranean flash-flood systems [1, 15].

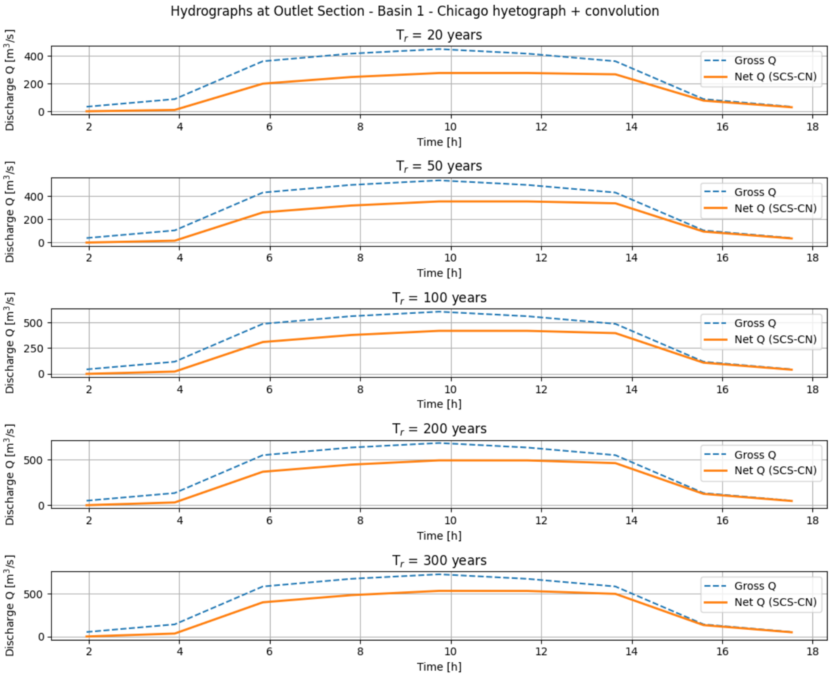


Figure 6: Design flood hydrographs at the outlet section of Basin ID: 2.

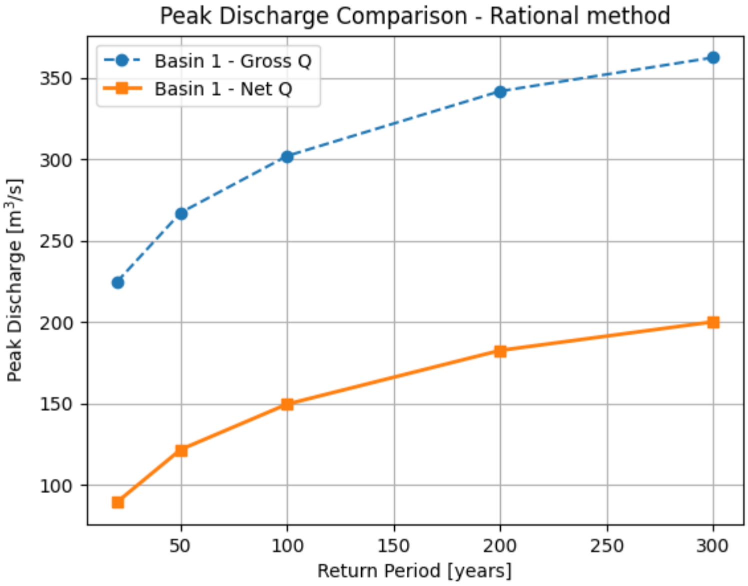


Figure 7: Design flood hydrographs demonstrating rapid temporal responses in headwater catchments.

6.3. Comparison with the literature and interpretive discussion

These findings corroborate the broader literature on open-source hydrological modeling. Operational hydrology significantly benefits from integrated environments where spatial data and mathematical algorithms are deterministically linked [9, 10, 11, 12]. A crucial implication of this study is that in ungauged catchments—where empirical calibration cannot compensate for poor process representation—model structure is paramount. The deliberate combination of regional rainfall analysis, distributed runoff abstraction, and time-area routing constitutes a scientifically defensible approach that physically mirrors flood generation mechanics in steep Mediterranean topography.

7. Limitations and Practical Considerations

The framework remains subject to inherent methodological limitations. The precision of the outputs is heavily contingent upon the resolution of the input DEM and the accuracy of the underlying pedological/land-use databases. Additionally, the empirical SCS-CN method lacks the capacity to simulate transient infiltration physics or detailed antecedent soil moisture evolution [15, 20]. Finally, time-area routing relies strictly on an idealized characterization of isochrone geometry. Given these uncertainties, the framework should be employed as a structured decision-support tool to evaluate relative scenarios rather than as a generator of absolute deterministic truths [3, 7].

8. Operational Implications for Flood Risk Management

This automated workflow carries direct and immediate implications for territorial planning and disaster risk reduction. Regional agencies mandated to assess vast numbers of ungauged catchments can leverage this QGIS-based framework to minimize manual effort and guarantee internal consistency across large-scale flood hazard mapping initiatives [9, 12]. Furthermore, as new climatological parameters emerge, the regionalization inputs can be effortlessly updated, positioning this tool as a highly adaptive instrument for ongoing climate resilience planning [8, 7].

9. Conclusions

This research presented an automated, GIS-based hydrological framework designed specifically for flood hydrograph estimation in ungauged Mediterranean catchments. By integrating regional frequency analysis, spatially distributed SCS-CN abstraction, and time-area routing via the PyQGIS API, the framework transforms disparate geospatial datasets into reproducible and highly informative design hydrographs.

From a scientific standpoint, the study advances the paradigm of open-source hydrology by delivering a cohesive, end-to-end model chain. From an operational perspective, it offers engineers and planners a scalable, robust tool uniquely tailored to combat the complex realities of flash-flood modeling in data-scarce regions. Future research trajectories will focus on quantifying input uncertainty, integrating automatic calibration modules for partially gauged basins, and coupling the derived hydrographs with 2D hydraulic inundation models.

Data Availability Statement

All datasets used in this study were obtained from publicly available sources or generated during the analyses described in the manuscript. Additional information is available from the author upon reasonable request.

Code Availability Statement

The PyQGIS workflow and computational procedures described in this manuscript are available from the author upon reasonable request.

Conflict of Interest

The author declares no conflict of interest.

Funding

This research received no external funding.

References

[1] A. Cuomo and D. Guida, “Hydro-Geomorphologic-Based Water Budget at Event Time-Scale in a Mediterranean Headwater Catchment (Southern Italy),” *Hydrology*, vol. 8, no. 1, 2021.

[2] E. Alshammari et al., “Investigation of Runoff and Flooding in Urban Areas based on Hydrological Models: A Literature Review,” *International Journal of Geoinformatics*, 2024.

[3] A.-P. Theochari, *Development and implementation of methodological framework towards flood risk management in ungauged basins.* Ph.D. Thesis, National Technical University of Athens, 2024.

[4] S. Sarchani, K. Seiradakis, P. Coulibaly, and I. Tsanis, “Flood Inundation Mapping in an Ungauged Basin,” *Water*, vol. 12, no. 5, p. 1532, 2020.

[5] A. Petroselli et al., “Modelli afflussi-deflussi per piccoli bacini idrografici non strumentati,” technical scientific contribution, 2019.

[6] A. Forestieri, F. Lo Conti, S. Blenkinsop, H. J. Fowler, and L. V. Noto, “Regional frequency analysis of extreme rainfall in Sicily (Italy),” *International Journal of Climatology*, vol. 38, no. 11, pp. 4036–4054, 2018.

[7] D. Treppiedi, A. Francipane, and L. V. Noto, "Valutazione delle curve di probabilità pluviometrica per il XXI secolo in Sicilia," *Proceedings of IDRA 2024*, 2024.

[8] Regione Siciliana, *Relazione analisi trend climatico.* Technical report, Palermo, Italy.

[9] C. Cîmpianu and A. Mihu-Pintilie, "Open Source Flood Mapping Tools – QGIS, RiverGIS and HEC-RAS," *Acta Geobalcanica*, 2019.

[10] S. Manfreda et al., "GFA tool – Geomorphic Flood Area tool," HydroLAB open-source QGIS plugin documentation.

[11] Trento Basin Authority, "Modellazione idrologica con AdB-Toolbox," open-source GIS procedure documentation, 2019.

[12] QGIS Plugin Repository, "Rain to Flood Analysis," open-source plugin documentation, 2026.

[13] K. Risva, *Development of a distributed hydrological software application employing novel velocity-based techniques.* Master Thesis, National Technical University of Athens, 2018.

[14] A. Francipane, G. Cipolla, D. Treppiedi, and L. V. Noto, "Integrated hydrological modeling and analysis tool for automatic derivation of design floods in Sicilian watersheds," *Environmental Modelling & Software*, vol. 191, 2025.

[15] Soil Conservation Service, *National Engineering Handbook, Section 4: Hydrology.* USDA, Washington, DC, 1972.

[16] GEOSTRU, "Teoria e definizioni: Modello SCS-CN," technical software documentation.

[17] Hydronline, "Onda di piena SCS-CN," online hydrological application documentation.

[18] J. Huang et al., "Synthetic hyetograph design and its influence on flood hydrograph estimation," hydrological modeling literature, 2023.

[19] U.S. Army Corps of Engineers, Hydrologic Engineering Center, "Unit Hydrograph Basic Concepts," technical documentation.

[20] A. Di Lazzaro and coauthors, "Green-Ampt Curve-Number mixed procedure as an empirical tool for rainfall-runoff modelling in small and ungauged basins," *Hydrological Processes*, 2012.