



Integrating satellite-based soil moisture within a rainfall-runoff database for operational flood forecasting in Mediterranean catchments

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Abstract. Flood forecasting in Mediterranean catchments is challenging due to strong rainfall variability and rapidly evolving antecedent wetness conditions. These challenges are further amplified in data-scarce basins, where limited hydrometric observations constrain the application of conventional real-time forecasting approaches. This study develops a probabilistic Rainfall-Runoff Database (RRDB) for the Crati River basin (2440 km²) in Calabria, southern Italy. The framework combines stochastic rainfall and air-temperature generation with a continuous semi-distributed hydrological model to generate, offline, a large ensemble of precomputed hydrographs spanning different event durations, precipitation amounts, and antecedent soil moisture conditions. The RRDB is evaluated across the three gauging sections in the study basin: Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari using observations of precipitation, satellite soil moisture and streamflow. The stochastic rainfall generator reproduces the main statistical properties and extremes of observed precipitation, while the hydrological model performs well across the evaluated gauging stations, with Nash-Sutcliffe efficiency (NSE) = 0.85 and Kling-Gupta efficiency (KGE) = 0.93 at the Sibari calibration section. Independent comparison of the modelled soil moisture with Advanced SCATterometer (ASCAT) satellite observations yields correlation coefficients of 0.50–0.72 across the three sub-catchments, supporting the use of satellite observations to characterize basin antecedent wetness conditions. Event-based validation shows that most observed hydrographs, peak discharges, and runoff volumes fall within or close to the corresponding RRDB probabilistic envelopes, although some extreme peaks are underestimated. The RRDB is evaluated in operational mode during the February 2026 flood event through its integration into HYPES (Hydro Prediction Engine System), an operational decision-support and flood forecasting platform. In this setup, forecast rainfall and satellite-derived surface soil moisture are used to identify representative precomputed scenarios within the RRDB and retrieve probabilistic discharge forecasts in real time. At Sibari, the observed peak discharge of 663 m³ s⁻¹ falls within the interquartile range of the retrieved probabilistic forecast (497–840 m³ s⁻¹), with an expected value of 674 m³ s⁻¹.



1 Introduction

30 Floods, particularly flash floods, are considered among the most destructive natural hazards worldwide, causing severe damage to infrastructure, ecosystems, and human communities (Smith and Ward, 1998; Villarini et al., 2010). Evidence from recent studies indicates changes in both the frequency and magnitude of hydrological extremes across many regions of the world, driven by the combined influence of climate variability and anthropogenic factors such as land use change (Wang et al., 2026; Sharma and Sharma, 2025; Zhan et al., 2025). Variations in precipitation and air temperature regimes have been linked to
35 changes in streamflow variability and to the occurrence of both flood and drought events, highlighting the sensitivity of hydrological systems to climatic forcing.

These evolving conditions represent significant challenges for flood risk management and highlight the need for reliable forecasting systems capable of providing timely and accurate early warnings to reduce potential losses (Damle and Yalcin, 2007; Cloke and Pappenberger, 2009; Silvestro et al., 2019). Flood forecasting systems (FFSs) aim to simulate and predict
40 river discharge and flood events by coupling meteorological forecasts with hydrological modelling. Achieving an effective forecast requires not only an accurate representation of rainfall spatial and temporal variability, but also a correct characterization of antecedent catchment wetness conditions (Brocca et al., 2008; Merz and Blöschl, 2009; Penna et al., 2011, 2015; Massari et al., 2023, Kirchner, 2024). These requirements become particularly critical in fast-responding and data-scarce catchments, where highly variable hydrological responses, strong rainfall heterogeneity, and limited observational data amplify
45 the impact of even minor inaccuracies in model inputs and initial conditions (Marchi et al., 2010; Borga et al., 2011; Merheb et al., 2016).

In this context, several studies have explored database-driven forecasting approaches based on libraries of precomputed rainfall-runoff simulations, allowing the rapid identification of plausible hydrological responses under different rainfall and soil moisture conditions without the need for real-time model execution (e.g., Brocca et al., 2013; Löwe et al., 2014; Löwe et al., 2016). Early applications demonstrated the potential of the approach for flood risk assessment and decision support in the
50 Elbe River basin (Liersch and Volk, 2008) and the Tiber River basin (Brocca et al., 2013). More recent developments extended this concept to real-time applications through hybrid historical-synthetic runoff databases, which increase the diversity and realism of simulated hydrographs, thereby improving the robustness of flood predictions, as demonstrated for catchments in Northern Italy (Crotti et al., 2019). Similarly, the database-driven approach has also been extended to offline flood forecasting
55 frameworks based on pre-simulated hydrodynamic models (Bhola et al., 2018).

Despite these advances, most existing implementations have been developed for relatively large and well-instrumented basins, where dense hydrometric and meteorological networks support both model calibration and the continuous estimation of basin state variables in space and time. This requirement limits their applicability in data-scarce catchments, where the lack of ground observations hampers the reliable estimation of antecedent wetness conditions, which strongly influence runoff generation and
60 flood response (Camici et al., 2011; Massari et al., 2023). As a result, the operational implementation of database-driven forecasting systems remains challenging in many ungauged or poorly monitored basins.



Satellite-derived soil moisture observations offer a promising opportunity to overcome this limitation by providing spatially consistent and operational estimates of catchment wetness, independent of dense in situ monitoring networks. Their routine availability makes them particularly attractive for lightweight forecasting systems designed for operational flood early warning in data-scarce regions. However, to the best of our knowledge, no previous study has integrated satellite-derived soil moisture observations into a precomputed rainfall–runoff database to define the initial hydrological conditions in an operational forecasting framework. This represents a critical gap in the development of computationally efficient, uncertainty-aware flood forecasting systems for poorly monitored catchments.

To address this gap, we investigate the use of satellite-derived surface soil moisture observations within an operational, database-driven flood forecasting framework, in which antecedent catchment conditions can be defined either from continuous hydrological model simulations or directly from satellite retrievals. Specifically, the work addresses the following research questions: (i) can satellite-derived surface soil moisture reliably characterize antecedent catchment wetness conditions compared to model-simulated soil moisture in a data-scarce Mediterranean catchment? (ii) can this satellite-derived information be used to select representative precomputed hydrological scenarios from the Rainfall-Runoff Database (RRDB), providing probabilistic river discharge forecasts without real-time model execution? and (iii) can this approach provide accurate and timely flood forecasts, particularly with respect to peak discharge, runoff volume, and forecast lead time?

The present study focuses on the Crati River basin (2440 km²) in Calabria, southern Italy, where severe flood events have repeatedly underscored the need for reliable forecasting and early-warning tools. While the framework is developed and evaluated in a single basin, its reliance on globally available satellite soil-moisture observations and a stochastic weather generator reduces its dependence on dense in situ monitoring networks and catchment-specific meteorological records, supporting its potential transferability to other data-scarce and poorly monitored catchments. The combination of satellite-based information on antecedent wetness and synthetic weather generation provides a consistent framework for characterizing both initial hydrological conditions and rainfall forcing, which is particularly relevant in regions where long-term ground-based observations are sparse or unavailable.

The remainder of this paper is organized as follows: Sect. 2 describes the methodology, including the study area, the datasets, the stochastic weather generators, the hydrological model, and the construction of the RRDB; Sect. 3 presents the results, covering the validation of the stochastic generation, the hydrological model, and the RRDB, together with the application to the February 2026 flood event; and Sect. 4 summarizes the main findings and conclusions.

2 Methods

2.1 Probabilistic rainfall-runoff database

The probabilistic Rainfall-Runoff Database (RRDB) is defined here as a precomputed archive of synthetic discharge hydrographs, generated offline by systematically combining a wide range of rainfall-event scenarios with different antecedent soil-moisture conditions through continuous hydrological simulation. Rather than running the hydrological model in real time,



RRDB allows the rapid retrieval of the most representative simulated responses for given rainfall and wetness conditions, providing probabilistic river discharge forecasts with minimal computational effort.

This design allows the RRDB to be integrated into real-time forecasting systems. Its implementation within an operational flood forecasting platform is described in detail in a dedicated study (Ruga et al., 2026), while an application to a real flood event is presented in Sect. 3.4.

The general workflow adopted for the construction of RRDB is summarized in Fig. 1 and consists of the following steps:

1. Generation of synthetic hydro-meteorological forcing. Stochastic weather generators are used to produce long-term hourly rainfall and air-temperature series representative of the basin's hydro-climatic variability, providing a large set of physically plausible forcing conditions.

2. Calibration and validation of the hydrological model. The continuous semi-distributed MISDc model (Camici et al., 2025) is calibrated using available hydro-meteorological observations. Model performance is then evaluated against river discharge observations at multiple control sections and further assessed against independent variables, such as relative surface soil moisture, not directly included in the calibration procedure.

3. Identification of weather scenarios. Independent rainfall events and the corresponding air-temperature series are extracted from the continuous synthetic records through a threshold-based procedure based on minimum rainfall depth and inter-event time criteria, allowing to define a set of representative weather scenarios.

4. Definition of antecedent catchment conditions. A wide range of initial soil-moisture states is considered to represent the full spectrum of antecedent basin wetness conditions and their influence on runoff generation processes. In operational applications, satellite-derived soil moisture observations are used to identify the subset of database scenarios most consistent with the current basin's wetness conditions.

5. Simulation of rainfall-runoff hydrological response. The hydrological model is executed for every combination of weather scenario and antecedent soil-moisture condition, generating an ensemble of synthetic discharge hydrographs that constitute the RRDB.

The transformation of continuous synthetic series into independent rainfall-runoff scenarios, together with a systematic representation of antecedent catchment conditions, forms the basis for database construction. These elements define the simulation space within which the basin response is characterized across a range of hydro-meteorological configurations.

The resulting database consists of a large collection of synthetic rainfall-runoff simulations describing catchment response over a broad spectrum of hydro-meteorological forcing and antecedent wetness conditions. For each simulation, the complete discharge hydrograph is stored, together with derived quantities such as peak flow, event runoff volume, and time to peak, enabling a probabilistic characterization of flood response across a wide range of physically plausible scenarios.

The following subsections describe the stochastic weather generators, the hydrological model, the study area, and the datasets used in this work.

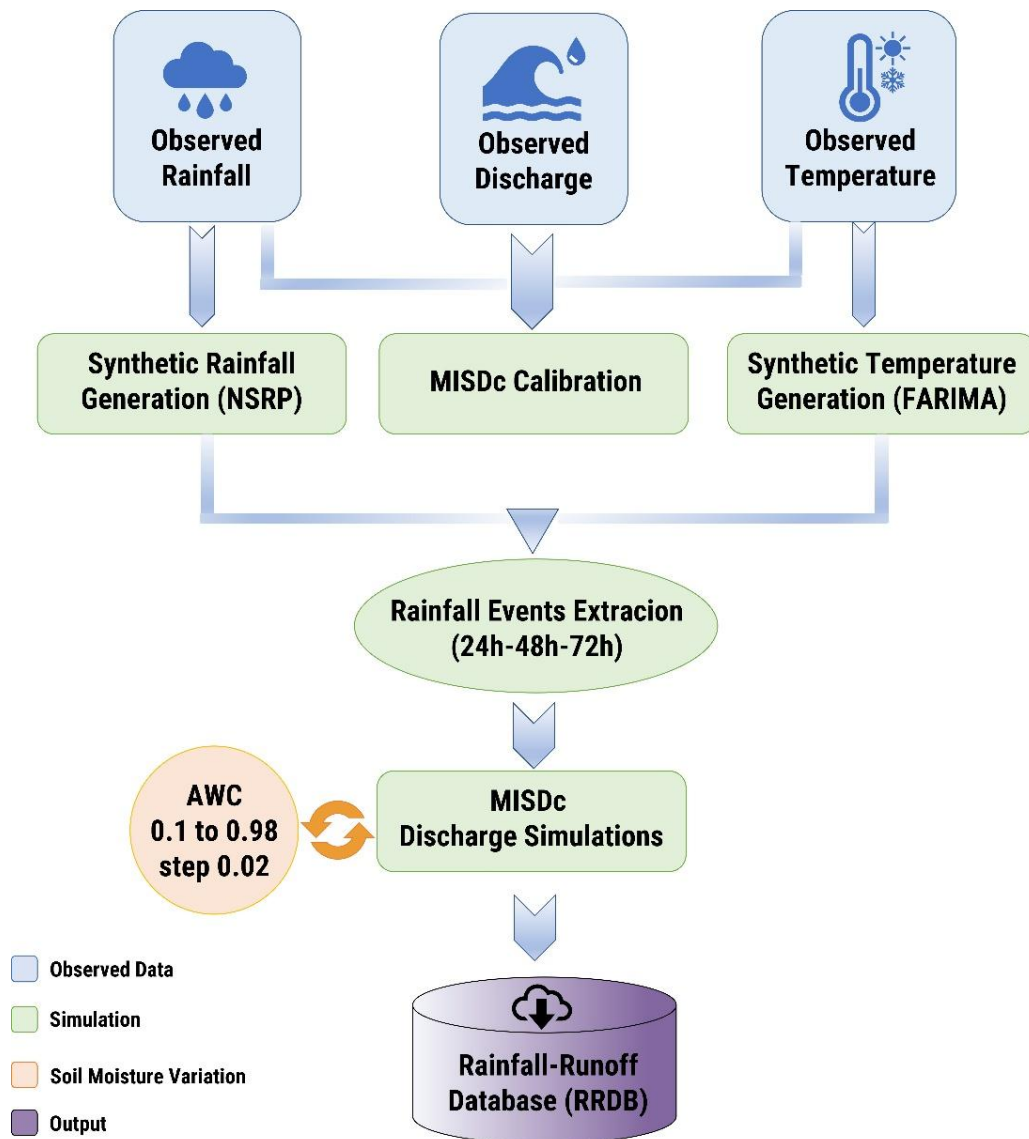


Figure 1: Schematic overview of the methodological framework used for the construction of the probabilistic rainfall runoff database.

130 2.1.1 Stochastic weather generators and hydrological modelling

In the proposed framework, rainfall and air temperature are generated independently by using two stochastic generator models. Consequently, their physical dependence is not explicitly represented in the simulations. The potential influence of this assumption on the simulated flood response is subsequently evaluated through a dedicated sensitivity analysis and discussed in Sect. 3.2.1.



135 **NSRP-IC Stochastic rainfall model**

Rainfall is simulated using a Neyman–Scott Rectangular Pulse model (NSRP, Cowpertwait et al., 1996), a stochastic point-process-based rainfall generator coupled with the Iman–Conover (IC) method for spatial correlation preservation (Tarpanelli et al., 2012).

140 The NSRP model represents rainfall as a sequence of storms whose origins follow a Poisson process. Each storm contains a random number of rain cells, occurring at exponentially distributed time intervals from the storm origin. Every cell generates a rectangular rainfall pulse, characterized by its duration and intensity, both modelled as exponential random variables. The total rainfall intensity at any given time is obtained as the sum of active cells, providing a realistic description of the temporal clustering and variability of rainfall.

145 The NSRP model is defined by five parameters describing storm arrival, cell occurrence rate, cell duration, cell intensity, and storm clustering. Parameter estimation is performed using observed hourly rainfall data by minimizing the weighted sum of normalized residuals between observed and theoretical statistical descriptors, including the mean, variance, autocorrelation, and intermittency of rainfall (Camici et al., 2011).

Once calibrated, the NSRP model is used to generate long-term hourly rainfall time series, independently at each location, reproducing the main statistical characteristics of the observed rainfall process across multiple temporal scales.

150 To preserve the spatial dependence structure of precipitation, the synthetic NSRP rainfall series are subsequently post-processed using the IC method (Iman and Conover, 1982). This rank-based reordering approach preserves the marginal rainfall distributions generated by the NSRP model while reproducing the observed spatial correlation structure among rainfall time series at different locations (Tarpanelli et al., 2012).

155 This stochastic rainfall generation framework provides a large ensemble of physically consistent rainfall scenarios, which are essential for developing the probabilistic RRDB and assessing the hydrological response of the basin under variable meteorological conditions.

FARIMA air temperature model

Hourly air temperature time series are generated using a Fractionally differenced ARIMA model (FARIMA, Montanari et al., 1997), a stochastic approach capable of reproducing the long-term persistence and slowly decaying autocorrelations characteristic of air temperature time series, also known as the Hurst effect (Hurst, 1951; Moretti and Montanari, 2008). Model implementation comprises seasonal adjustment of the observed air-temperature series, parameter estimation, and validation of the simulated data against the observed statistical characteristics. The calibrated FARIMA model is then used to generate long-term synthetic hourly air-temperature series that reproduce the observed seasonal variability and long-range persistence, providing physically consistent air temperature forcing for the hydrological simulations.

165 **MISDc hydrological model structure and configuration**

MISDc (Brocca et al., 2011; Massari et al., 2018; Camici et al., 2025) is a conceptual, semi-distributed, continuous hydrological model designed to reproduce soil moisture dynamics and runoff generation at the catchment scale. By using rainfall and air temperature data as input, it explicitly represents the main components of the water balance, including infiltration,



evapotranspiration, surface runoff, and subsurface flow. In particular, the model structure enables the continuous simulation of catchment wetness and allows the model to represent how antecedent soil moisture conditions affect runoff generation, resulting in consistent flood hydrograph simulations. The soil module is structured into two layers representing shallow and deeper soil moisture storage; this distinction is particularly relevant when comparing model outputs with satellite-derived soil moisture products, as these typically capture only the shallow soil moisture dynamics (approximately the upper 0–15 cm), corresponding to the model's upper layer.

The conceptually simple structure and proven reliability in simulating hydrological processes, also under limited data availability (Brocca et al., 2020; Ait Naceur et al., 2026), makes the MISDc model ideal for data-scarce basins. Furthermore, the model's design enables integration with satellite-derived rainfall and soil moisture datasets (see, e.g., Massari et al., 2018) extending its usability to operational flood forecasting frameworks that rely on remote sensing information.

Detailed model description and the modules used to represent the hydrological cycle can be found in Camici et al. (2025). In this study, MISDc is applied in event-based mode to simulate only the direct runoff response. For a consistent comparison between observed and simulated hydrographs, the initial river discharge observed immediately before each event (Q_0) was subtracted from the observed hydrographs, so that both simulated and observed hydrographs represent only the event-driven runoff component.

2.2 Study area

The Crati River basin is located in northern Calabria (southern Italy) and drains an area of approximately 2440 km² upstream of the hydrometric section of Sibari (Figure 2). The river originates from the Sila plateau, at an average elevation of 1200–1300 m a.s.l., and flows north-westward towards Cosenza, where it joins the Busento River and substantially increases its contributing area. Downstream of Cosenza, the Crati traverses a wide alluvial plain before discharging into the Ionian Sea. The basin is characterized by complex mountainous and hilly terrain, with steep topographic gradients in the headwaters and extensive low-lying areas in the downstream sector.

The climate is Mediterranean, with pronounced spatial variability associated with elevation, orography, and proximity to the Ionian Sea. Mean annual precipitation across the basin is slightly below 1000 mm yr⁻¹, ranging from just above 500 mm yr⁻¹ near the outlet to more than 2000 mm yr⁻¹ in the mountainous sectors. Three main pluviometric zones can be distinguished in the upland areas: (i) a western sector receiving approximately 1500 mm yr⁻¹; (ii) an eastern sector with mean annual precipitation of about 1100 mm, decreasing to approximately 800 mm at lower elevations; and (iii) the northern slopes of the Pollino massif, where precipitation ranges between 800 and 1300 mm depending on altitude (Callegari et al., 2011). Mean annual temperature varies from approximately 14.0 to 14.7 °C, with lower temperatures at higher elevations. This climatic and topographic heterogeneity strongly influences runoff generation and flood propagation across the basin.

The Crati exhibits a predominantly torrential hydrological regime, characterized by a rapid response to rainfall, generally within 2–4 h (Spada et al., 2017), marked seasonality, and strong intermittency. Extended low-flow or near-dry conditions during summer frequently alternate with short-duration, high-intensity rainfall events capable of triggering sudden floods.



Such behaviour is typical of Mediterranean catchments and reflects the combined effects of rainfall seasonality, convective storm activity, and pronounced topographic gradients (e.g., Gaume et al., 2009; Marchi et al., 2010; Llasat et al., 2010). The rapid concentration of runoff from the mountainous headwaters can produce sharp increases in downstream discharge, whereas
205 prolonged stratiform precipitation affecting a large portion of the basin may result in sustained high flows in the downstream alluvial plain.

The basin has experienced several severe flood events, highlighting its vulnerability, particularly in the downstream alluvial plain. Notable events include the disastrous winter floods of the 1950s and major floods in December 2008 and 2013, which affected urban areas such as Cosenza and culturally significant sites including the archaeological site of Sibari. More recently,
210 in February 2026, several days of persistent rainfall resulted in critical river discharges and localized flooding, including in the area of Cassano allo Ionio in the Sibari plain. The alternation between prolonged drought periods and extreme flood events further contributes to hydroclimatic stress and geomorphological instability (Polemio et al., 2004).

Anthropogenic changes have further influenced runoff generation and flood propagation. Urban expansion in the Cosenza area, localized river-training works, small hydraulic structures, and progressive land-use changes have modified the
215 hydrological and hydraulic response of the basin (De Bonis et al., 2017). These pressures interact with the basin's natural climatic and geomorphological variability, contributing to complex spatial and temporal patterns of flood occurrence.

Overall, the combination of pronounced climatic variability, complex topography, rapid hydrological response, and anthropogenic pressures makes the Crati River basin a representative and challenging case study for flood-risk assessment in Mediterranean regions.

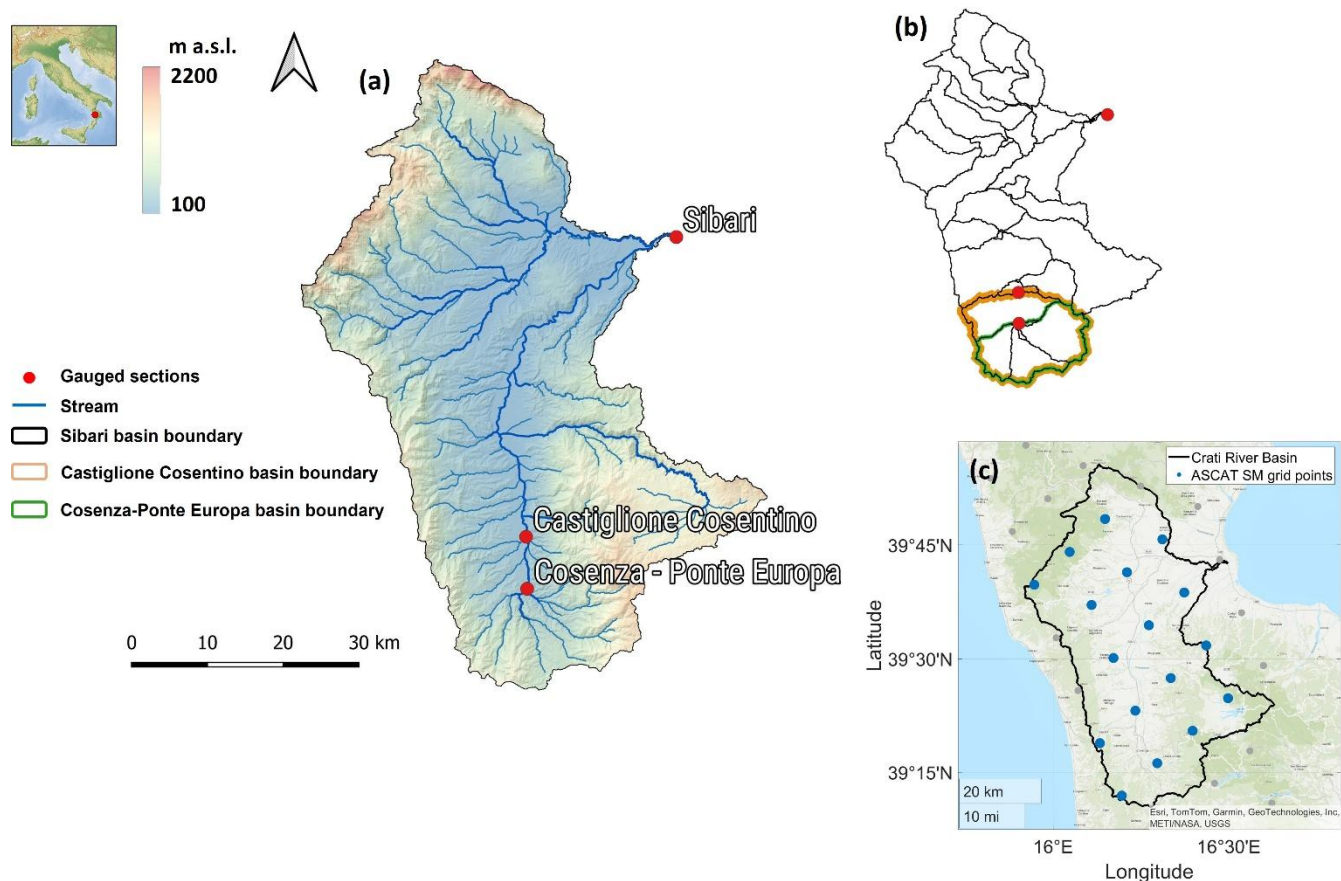


Figure 2: (a) Crati River basin, Calabria (southern Italy). The main river network and the location of the gauging sections are illustrated. (b) a detailed view of the basin division into 35 sub-basins and the three sub-catchments corresponding to the gauging sections considered in this study, located near Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari. (c) map of the Crati River basin showing the selected ASCAT grid points used for soil moisture comparison with MISDc simulations. Map data in (c): sources Esri, TomTom, Garmin, GeoTechnologies Inc., METI/NASA, USGS.

2.3 Data description

The data used in this study are rainfall, air temperature, river discharge records together with satellite-derived soil moisture observations. In addition, a digital elevation model (DEM) is used to define the river network topology.

Observed precipitation data are derived from the gridded precipitation dataset developed by the CIMA Research Foundation (Bruno et al., 2021). This dataset provides hourly rainfall fields at 1 km spatial resolution across Italy for the period 2010–2024 and is obtained through the merging and interpolation of rain gauge and weather radar observations. The integration of multiple data sources ensures spatial consistency and improved reliability, particularly in mountainous or sparsely instrumented areas. These data are part of a broader national scale hydrometeorological reanalysis framework designed to support flood and snow monitoring applications (Avanzi et al., 2023).



235 Consistent with the rainfall dataset, observed 2010–2024 hourly air temperature data were obtained from the CIMA gridded product, in which ground-based station records are spatialized as a function of elevation to produce spatially coherent air temperature fields over Italy (Avanzi et al., 2023). With respect to river discharge data, the Crati River basin is characterized by a sparse hydrometric monitoring network, with substantial differences in the quality and reliability of river discharge estimates among monitoring sites. Long-term semi-hourly water level records are available at the Sibari (2001–2025),
240 Castiglione Cosentino (2001–2025), and Cosenza-Ponte Europa (2010–2025) gauging stations (Fig. 2a). For the Castiglione Cosentino and Cosenza-Ponte Europa stations, river discharge estimates derived from stage-discharge rating curves are subject to considerable uncertainty, owing to the limited reliability of the rating relationships under varying hydraulic conditions (Spada et al., 2017). In contrast, the Sibari section, located at the basin outlet, represents the most reliable hydrometric site, thanks to the morphological stability of the channel cross-section and the continuity of observations, which enabled the
245 development of a robust and temporally stable rating curve.

To independently evaluate the soil moisture simulations produced by MISDc, the Advanced SCATterometer (ASCAT) satellite product distributed by the EUMETSAT H SAF (Support to Operational Hydrology and Water Management) programme is used. ASCAT provides surface soil moisture estimates based on C-band radar backscatter, retrieved through the well-established change detection algorithm (Wagner et al., 2013), which normalizes backscatter between dry and wet reference
250 conditions while accounting for vegetation dynamics.

For this study, we employ the H121 Level-3 soil moisture dataset, a harmonized long-term record integrating observations from the ASCAT sensors onboard the Metop-A, Metop-B, and Metop-C satellites. The product is provided on a regular grid with a spatial resolution of 12.5 km and a daily temporal frequency, offering consistent large-scale coverage suitable for basin scale hydrological applications. Because ASCAT expresses soil moisture in relative saturation units (0–100 %), the time series
255 is normalized to a common scale before comparison with the modelled basin averaged soil moisture.

The choice of ASCAT reflects its long observational record, stable retrieval algorithm, and proven skill in capturing soil moisture dynamics relevant for operational hydrological response analysis. The ASCAT dataset is extracted over the Crati basin and used to assess the temporal consistency between the modelled basin averaged soil moisture and satellite observations. This comparison provides an independent evaluation of the model's ability to simulate antecedent wetness conditions. A map
260 of the Crati basin with the selected ASCAT grid points is provided in Fig. 2c.

2.4 Framework modelling setup

Based on the DEM and the delineation procedure of Camici et al. (2022), the Crati River basin is subdivided into 35 sub-basins (Fig. 2b). Hourly rainfall and air temperature (2010–2024) are extracted and spatially averaged over each sub-basin by aggregating all grid cells within the corresponding boundaries, resulting in 35 representative hydro-meteorological time series.
265 The RRDB framework described in Sect. 2.1 is implemented for the Crati River basin following the procedure outlined below.

1. Stochastic hydro-meteorological generation and validation. The 35 observed rainfall series are used to calibrate the NSRP model. Ten independent 100-year hourly rainfall realisations are generated for each sub-basin, preserving observed



marginal statistics, temporal correlation, and intermittency. Spatial dependence is enforced using the Iman-Conover (IC) procedure. Air temperature is simulated via FARIMA model calibrated on the 35 observed series, generating ten hourly 100-year long realisations per sub-basin while preserving seasonal variability and long-range dependence.

2. The reliability of the synthetic hydro-meteorological forcing is assessed by comparing the generated series with observations over three representative sub-catchments draining to Cosenza-Ponte Europa, Castiglione Cosentino, Sibari (Figure 2b). For the purpose, synthetic rainfall and air temperature series are aggregated over each sub-catchment using inverse distance weighting (IDW). Rainfall is assessed in terms of monthly statistics (mean, variance, 24 h variance, autocorrelation) and annual maxima for 1, 6, 12, and 24 h durations. Air temperature is evaluated via monthly frequency distributions.

3. Hydrological model calibration and validation. The MISDc model is calibrated against river discharge at the Sibari outlet section and validated at two internal sections, Castiglione Cosentino and Cosenza-Ponte Europa. In addition to river discharge-based evaluation, the relative soil moisture dynamics simulated by MISDc are independently assessed through comparison with ASCAT H121 Level-3 satellite-derived soil moisture products. For each of the three representative sub-catchments (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari), both modelled and satellite-derived soil moisture are spatially aggregated over the corresponding contributing area to ensure spatial consistency. To ensure a physically consistent comparison, ASCAT surface soil moisture is compared with the upper MISDc soil layer only (approximately 0–15 cm; see Sect. 2.1.1), which captures the same shallow soil moisture dynamics observed by the satellite; no vertical filtering (e.g., exponential smoothing towards deeper layers) is therefore applied to ASCAT data. ASCAT observations are linearly rescaled to the mean and standard deviation of the modelled series to account for the different value ranges of the two products. Model performance in reproducing river discharge is evaluated using the Nash–Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970), the linear correlation coefficient (R), and the Kling–Gupta efficiency (KGE, Gupta et al., 2009), while the agreement between simulated and satellite-derived soil moisture is quantified in terms of R and root mean square error (RMSE).

4. Event extraction. Independent hydro-meteorological events are derived from synthetic rainfall and air temperature series using a threshold-based approach. The minimum inter-event time is set equal to the time of concentration of the basin (approximately 13 h, Gambini et al., 2024), meaning that rainfall periods separated by more than 13 consecutive dry hours are considered independent events. Within each event, short rainfall interruptions are allowed to account for intermittent rainfall patterns: dry periods shorter than 10 h are not considered sufficient to split an event, provided that at least 1 mm of rainfall occur within the surrounding 10 h period. Events with cumulative rainfall below 10 mm are discarded. According to these criteria, 20559 weather scenarios are identified, each consisting of a rainfall event with a duration ranging from 5 to 130 h and an associated air-temperature series. Although some events share the same total precipitation depth, they may differ substantially in their temporal rainfall distribution, leading to distinct hydrological responses.

5. Antecedent conditions. Initial relative soil moisture is systematically varied between 0.10 and 0.98 ($\Delta = 0.02$), defining 45 antecedent wetness states spanning dry to near-saturated conditions.



6. Rainfall-runoff simulations and RRDB construction and validation. Each weather scenario, together with the 45 prescribed initial relative soil moisture conditions, is used as input to the MISDC model to simulate the corresponding runoff response at the Sibari, Castiglione Cosentino, and Cosenza-Ponte Europa control sections. Three fixed event durations (24, 48, 72 h) are imposed by truncating weather scenarios beyond the selected duration. Therefore, 45×20559 simulations per duration and location are performed.

Specifically, the combination of (i) multiple stochastic rainfall realizations, (ii) a full spectrum of initial soil moisture states, and (iii) three characteristic storm durations produced a densely populated rainfall-runoff response space. This structure allows RRDB to represent the nonlinear interactions between event magnitude, rainfall temporal distribution, and antecedent catchment conditions with a high level of detail. Overall, the resulting database comprises thousands of synthetic rainfall-runoff events spanning a wide range of plausible hydrological scenarios, thereby providing a probabilistic characterization of the basin response.

3 Results

3.1 Stochastic hydro-meteorological generation and validation

3.1.1 Rainfall generation

The comparison between observed and simulated rainfall characteristics for the three control sub-catchments (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari; Fig. 3) shows that the NSRP-IC model can reproduce the main statistical and temporal properties of hourly precipitation across the Crati River basin. Panel (a) presents the comparison of first- and second-order rainfall statistics, including 24-h mean, 1-h variance, 24-h variance, and 24-h autocorrelation, while panel (b) compares observed and simulated annual maximum precipitation for durations ranging from 1 to 24 h, showing the capability of the model to represent extreme rainfall behaviour.

Overall, the parameter estimation and simulation framework provide consistent results across sub-basins, confirming the NSRP-IC model's ability to reproduce observed precipitation characteristics. These synthetic rainfall inputs thus support subsequent hydrological modelling and the development of the RRDB.

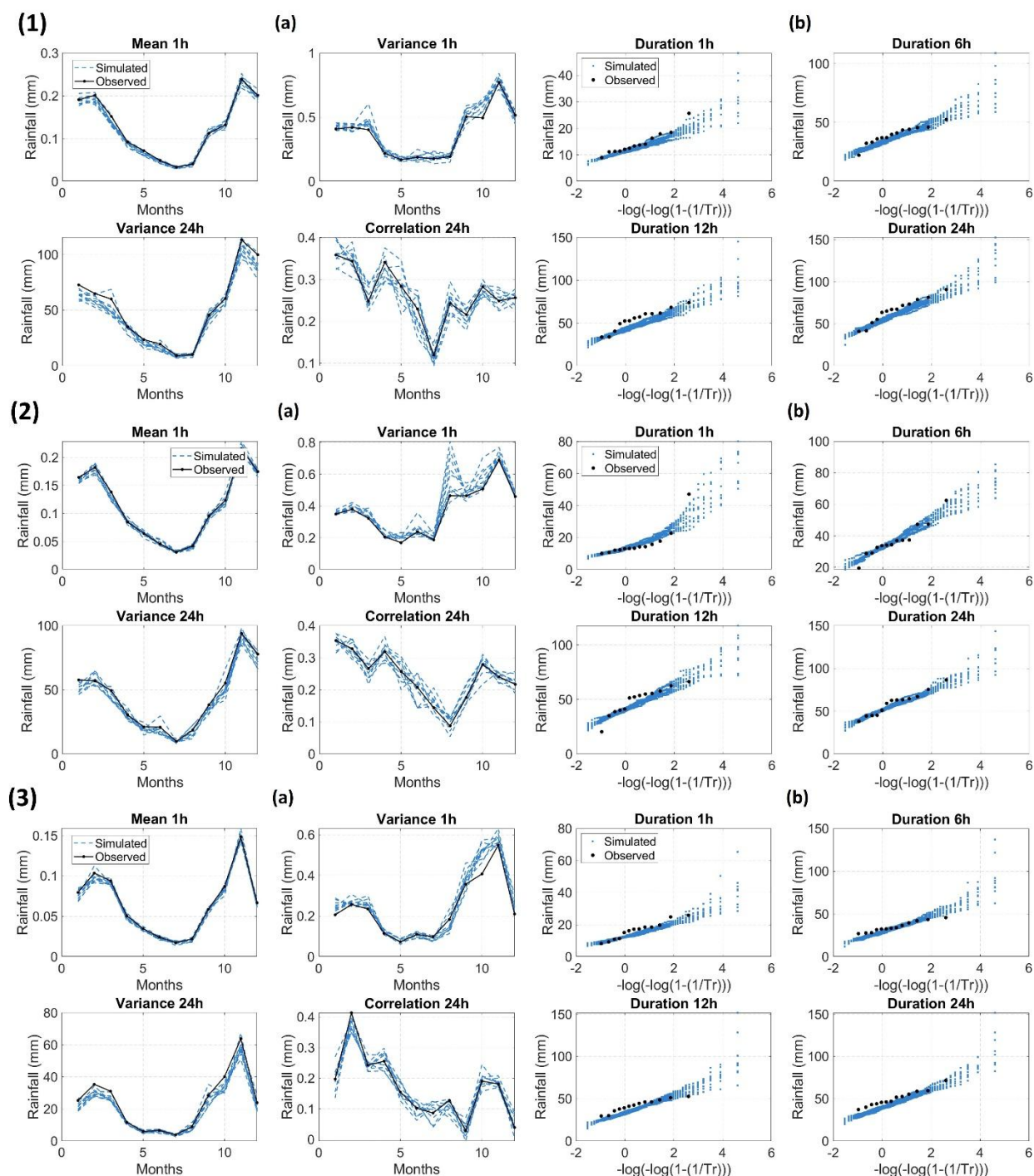


Figure 3: Comparison between the observed and synthetic rainfall data (10 runs) for three sub-catchments: (1) Cosenza-Ponte Europa, (2) Castiglione Cosentino, and (3) Sibari. Each sub-figure includes two panels: panel (a) reports the monthly evolution of rainfall characteristics, illustrating the temporal patterns and variability of observed versus simulated rainfall; panel (b) displays the annual maximum rainfall for durations between 1 h and 24 h.



330 **Air temperature generation**

Figure 4 compares observed and simulated air temperatures for the three sub-catchments draining to Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari gauging stations.

The FARIMA model accurately reproduces the monthly climatology of the basin. The agreement between observed and simulated distributions is consistent across the three sub-catchments, indicating that the stochastic model successfully
335 preserves the statistical characteristics of air temperature despite the marked climatic differences associated with the basin elevation gradient. At Cosenza-Ponte Europa the simulated distributions show a slightly lower peak and a larger spread than the observed ones. The central tendency of monthly air temperature distributions is well reproduced throughout the year. Overall, the FARIMA-generated air temperature fields provide statistically robust representations of the thermal regime, preserving both seasonal structure and variability, and constitute a physically consistent complement to the stochastic rainfall
340 realizations for the subsequent rainfall-runoff simulations.

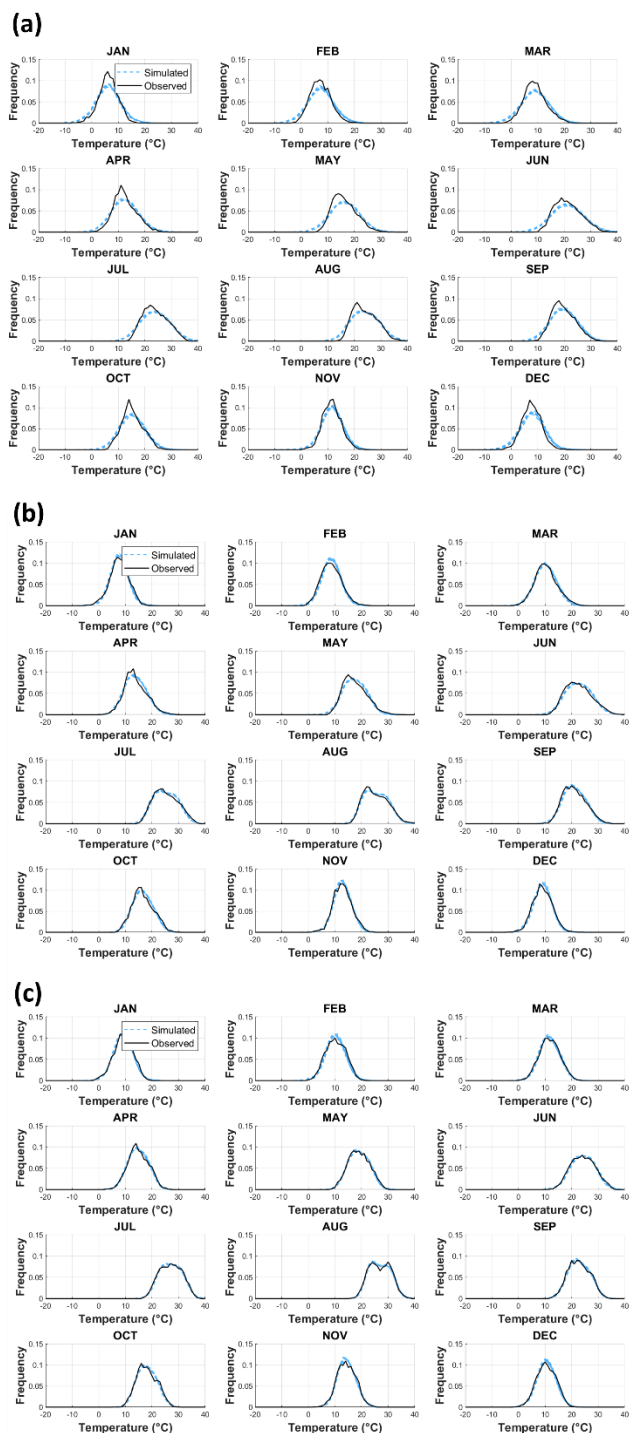


Figure 4: Monthly frequency distributions of observed and simulated hourly air temperatures for the three representative control sections of the Crati River basin: (a) Cosenza-Ponte Europa, (b) Castiglione Cosentino, and (c) Sibari.

3.2 Hydrological model calibration and validation

- Figure 5 shows the observed (Q_{obs}) and simulated (Q_{sim}) river discharge time series for the 2010–2025 period at the calibration station (Sibari) and the two independent validation stations (Castiglione Cosentino and Cosenza-Ponte Europa). Model performance is high throughout the calibration period at Sibari, with $NSE = 0.85$, $R = 0.93$, and $KGE = 0.93$ (Fig. 5, upper panel), indicating the model’s ability to accurately reproduce both the magnitude and timing of observed flows. At the two validation sections, performance is moderate but acceptable, reflecting the lower reliability of the observational datasets. At Cosenza-Ponte Europa, the model shows an NSE of -0.06 , an R of 0.79 , and a KGE of 0.39 , while at Castiglione Cosentino the corresponding values are an NSE of 0.24 , an R of 0.73 , and a KGE of 0.49 . These values reflect the combined effects of uncertainties in the rating curves, and thus in the observed river discharge, together with the influence of spatial heterogeneity in runoff generation on model response. Nevertheless, the MISDc model can adequately reproduce the main characteristics of the upstream flow regime.
- Over the entire hourly time series, MISDc reproduces the temporal variability of ASCAT H121 Level-3 soil moisture (Fig. 6), with R values of 0.84 at the basin scale (Sibari) and 0.77 – 0.78 at the two internal sub-catchments.

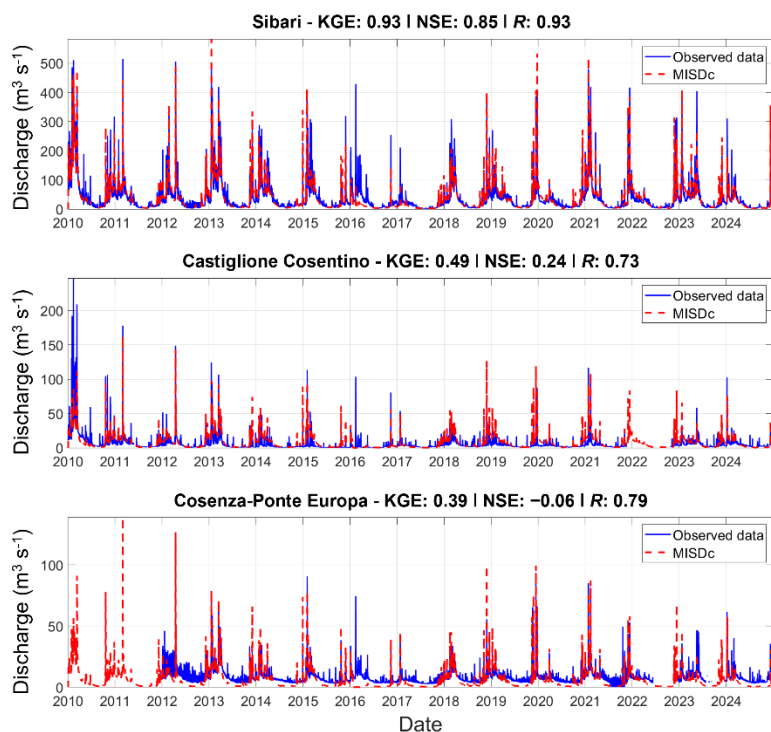


Figure 5: Time series of observed (Q_{obs}) and simulated (Q_{sim}) river discharge at Sibari (calibration section) and at Castiglione Cosentino, and Cosenza-Ponte Europa (independent validation sections).

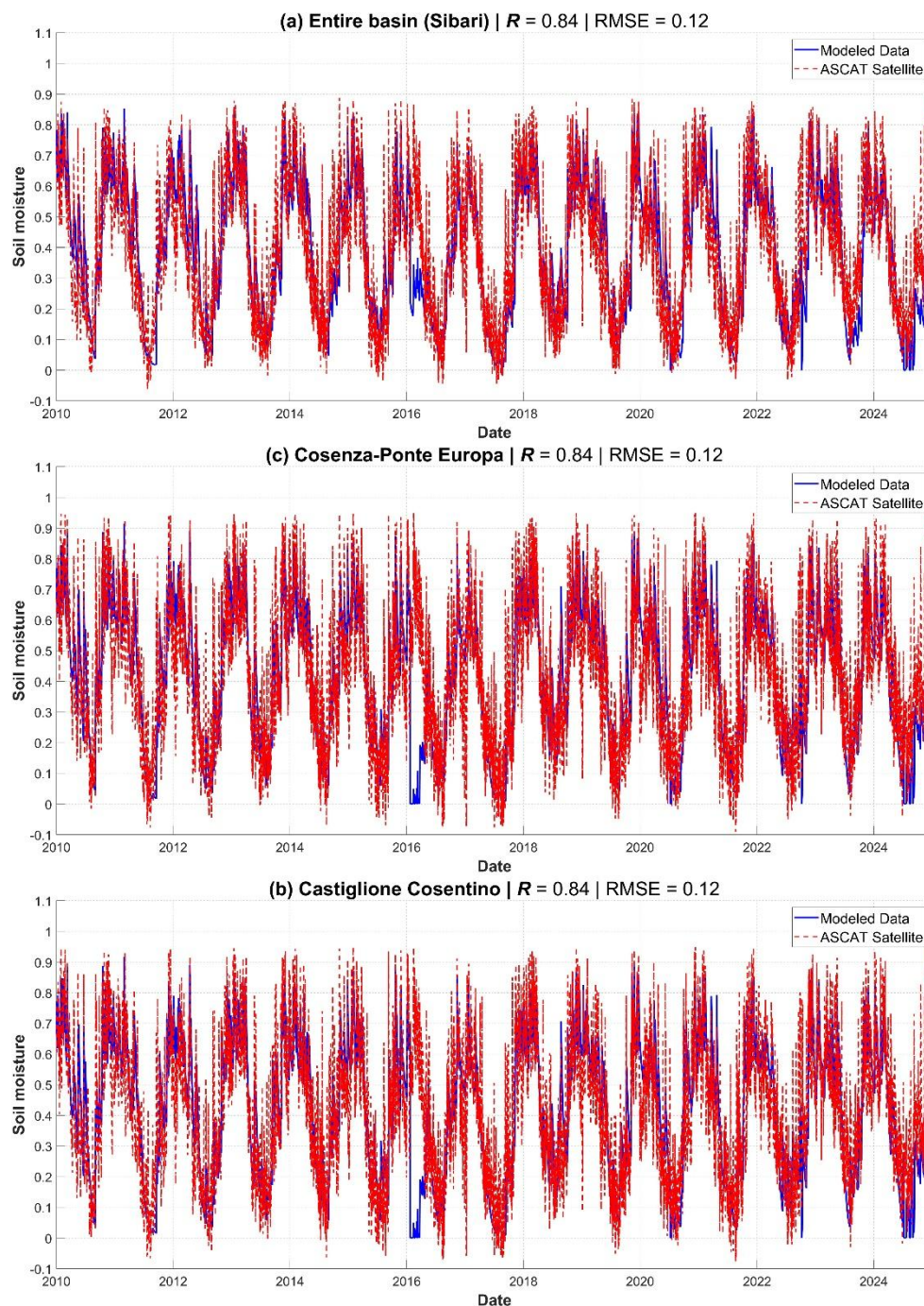


Figure 6: Basin-averaged soil moisture simulated by MISDc compared with ASCAT H121 Level-3 observations over the 2010–2024 period. Panels represent: (a) the entire basin (closed at the Sibari section), (b) the sub-basin closed at Castiglione Cosentino, and (c) the sub-basin closed at Cosenza-Ponte Europa. The correlation coefficient (R) and root mean square error (RMSE) reported in each panel refer to the full hourly time series.



3.2.1 Rainfall–air temperature dependence: sensitivity analysis on flood modelling

Since rainfall and air temperature are generated independently (Sect. 2.1.1), the synthetic series do not reproduce the physical link between the two variables, whereby air temperature tends to decrease during rainfall, as directly observed in the Crati data and quantified in the following analysis. To assess whether neglecting this dependence could materially affect the simulated flood response, we used the observed rainfall and air temperature series for the Crati basin and quantified its potential impact on the water balance and, consequently, on the simulated river discharge for the observed rainfall events selected at the Sibari control section (Table A1).

Air temperature affects the MISDc model through two processes: the partitioning of precipitation into rainfall and snowfall in the snow module, and the estimation of evapotranspiration. The first process is not relevant for the events considered here, since approximately 90 % of the analysed events occur at air temperatures above the rain–snow threshold of +0.5 °C adopted in MISDc (Camici et al., 2025), so that precipitation is treated entirely as rainfall.

We therefore focused on the effect of air temperature on evapotranspiration. (i) For each event, we used the hourly air temperature averaged over the basin to calculate potential evapotranspiration (PET) using the air temperature-based Blaney–Criddle formulation adopted in MISDc. The formulation includes a calibration coefficient, b (Camici et al., 2025), which we set to its calibrated value of 1.5. We then accumulated PET over the event duration and compared it with the corresponding event rainfall. On average, PET accounts for approximately 8 % of event rainfall.

(ii) We then quantified the magnitude of the rainfall-associated air temperature decrease using the observed data. For each month, we compared air temperature during rainy hours with that during dry hours, thereby removing the effect of the seasonal cycle. The resulting air temperature decrease ranged from 0.5 to 1.3 °C in the autumn–winter months, when all the analysed events occur, and reached approximately 3 °C in summer.

(iii) Finally, for each event, we recomputed PET after artificially removing the corresponding rainfall-associated air temperature decrease from the observed air temperature series. This provided an estimate of evapotranspiration under conditions in which the air temperature cooling associated with rainfall is absent, as in the synthetic series. We then evaluated the resulting change in the event water balance relative to event rainfall.

The overestimation of the event water balance averages about 0.6 % of event rainfall (and remains below 3.5 % for all events). Even for a hypothetical summer event, in which the air temperature decrease is largest (~3 °C), this overestimation would remain limited (of the order of 3 % of event rainfall), as potential evapotranspiration accounts for only a small fraction of event rainfall. These results indicate that neglecting the rainfall–air temperature dependence had a minor effect on the event water balance for the flood events analysed here.

Most importantly, air temperature influences the hydrological response mainly through the antecedent soil moisture state. In the RRDB, this state is not derived from the synthetic air temperature series, but it is prescribed systematically during database construction (Sect. 2.4) and constrained by satellite soil moisture observations in operational applications (Sect. 3.4). The



independent generation of rainfall and air temperature therefore does not compromise the ability of the RRDB to represent the flood response.

3.3 Validation of the rainfall-runoff database

Prior to its application for operational purposes, RRDB is validated against observed data through a two-level procedure to verify its ability to reproduce a broad spectrum of rainfall-runoff events consistent with those recorded in the Crati catchment. The first validation level concerns the rainfall component and verifies that the 20559 events extracted from the synthetic rainfall series span the variability of the observed rainfall regime, in terms of cumulative rainfall depth and event duration. Figure 7 first characterizes the range of simulated cumulative precipitation for the three event durations (24, 48, and 72 h) at the three study sites (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari) using violin plots, showing the rainfall variability spanned by the database across temporal scales and spatial locations.

Rainfall distribution (RRDB dataset)

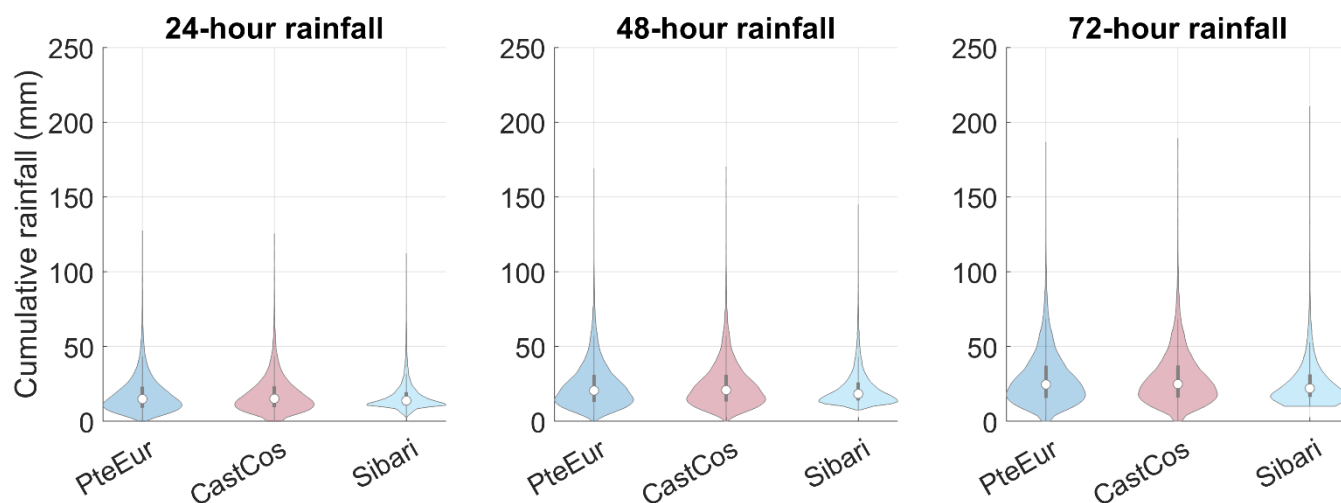


Figure 7: Violin plots of simulated cumulative rainfall distributions for 24, 48, and 72 h events at Cosenza-Ponte Europa (PteEur), Castiglione Cosentino (CastCos), and Sibari. The plots illustrate differences in distribution shape and variability across event durations and study sites.

The selection of observed rainfall events follows the same rainfall-threshold framework applied to the stochastic series (see Sect. 2.4). A set of observed rainfall events is selected for the three representative control sections (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari) from the available precipitation records. The dataset consists of 47 events at Cosenza-Ponte Europa, 60 events at Castiglione Cosentino, and 45 events at Sibari, corresponding to the main rainfall-runoff responses within the analysis period. Summary statistics of event duration, sub-basin cumulative rainfall, and antecedent relative soil moisture derived from both the hydrological model and ASCAT satellite observations are reported in Table 1, while the complete event-based datasets for each control section are provided in Appendix A (Tables A1, A2, A3).



Table 1: Summary statistics of rainfall events and soil moisture conditions for the three control sections. Event characteristics include the number of events, mean duration, and mean cumulative rainfall at the sub-basin scale. Soil moisture statistics and performance metrics (*R* and RMSE) quantify the agreement between MISDc-simulated and ASCAT-derived soil moisture.

Site	Events (n)	Mean duration (h)	Mean rainfall (mm)	Mean MISDc SM	Mean ASCAT SM	R (MISDc vs ASCAT SM)	RMSE (MISDc vs ASCAT SM)
Sibari	45	47.24	43.65	0.73	0.74	0.72	0.07
Cosenza-Ponte Europa	47	35.96	44.01	0.61	0.77	0.54	0.20
Castiglione Cosentino	60	39.35	42.98	0.68	0.76	0.50	0.13

425 Observed and simulated rainfall events are compared for Sibari section within the duration-cumulative rainfall space (Fig. 8a), allowing verification that the observed hydrometeorological conditions are consistently encompassed within the range of the stochastic climate space.

For the same section, event-scale hydrological responses are also evaluated by comparing observed and simulated discharge hydrographs obtained by forcing the MISDc model with synthetic rainfall. Figure 8b reports this comparison for three event
 430 duration classes (< 35 h, 35–50 h, > 50 h), highlighting the ability of the model to reproduce runoff dynamics across different rainfall temporal scales.

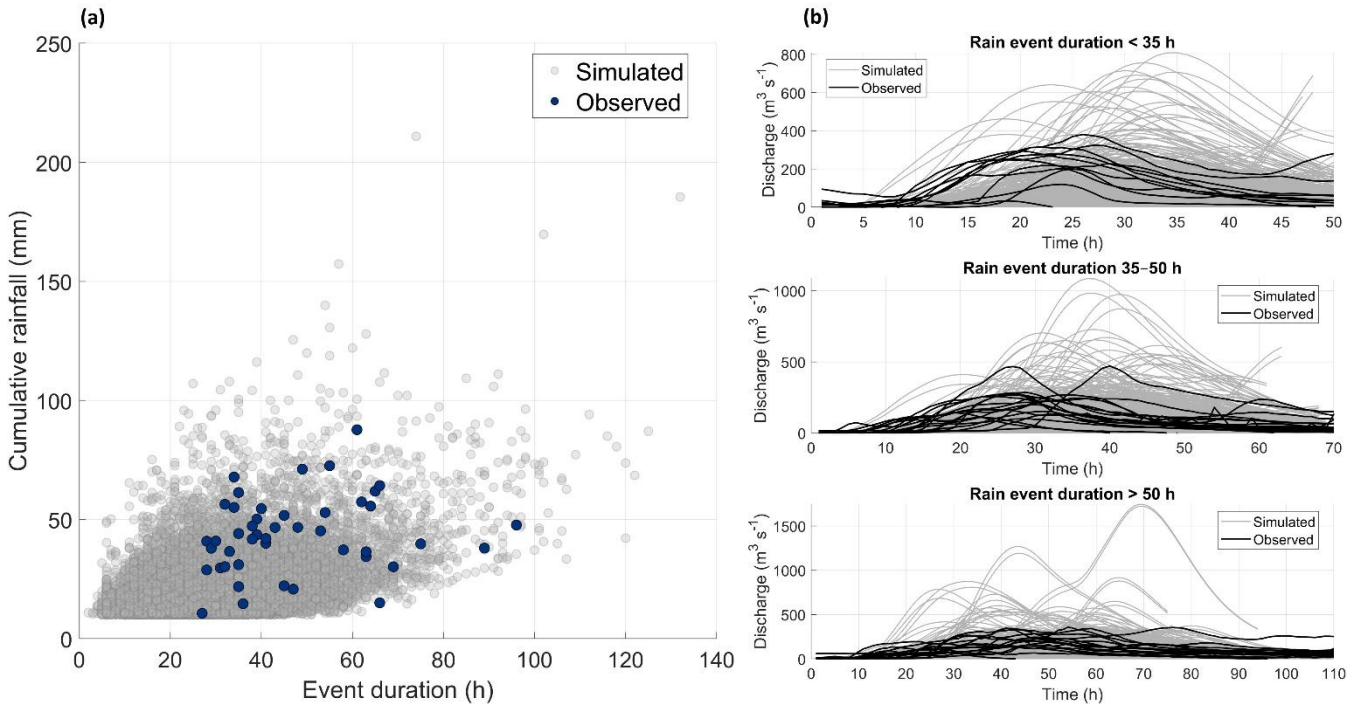


Figure 8: Sibari control section: (a) observed rainfall events compared with the full ensemble of simulated events in the duration–cumulative rainfall space. (b) Simulated discharge hydrographs (grey) compared with observed events (black) for three rainfall event duration classes: < 35 h, 35–50 h, and > 50 h (soil moisture = 0.5).

Overall MISDc, driven with synthetic weather scenarios, reproduces the main statistical properties and variability of observed rainfall-runoff responses at the event scale, providing a consistent basis for probabilistic hydrological analysis.

The second validation level assesses the consistency of RRDB across the three control sections (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari), focusing on the capability of the precomputed database to reproduce observed hydrological responses under real hydro-meteorological conditions. For consistency with the RRDB structure, a second selection of observed hydrographs is performed based on event duration (24, 48, and 72 h), applying a tolerance window to ensure enough events for robust comparison. Observed river discharge hydrographs are then extracted for each event, subtracting the initial pre-event discharge Q_0 to isolate the rainfall-driven runoff component.

The representation of antecedent soil moisture conditions is a key aspect of the validation. Because the RRDB explicitly organizes events according to initial soil moisture, each observed event is associated with a representative soil moisture state derived from MISDc simulations, spatially rescaled to the basin scale.

An independent comparison between ASCAT observations and relative soil moisture simulated in the upper MISDc soil layer shows moderate to good agreement, as illustrated by the scatterplots of modelled (MISDc) versus ASCAT SM values for the selected events (Fig. 9). The highest agreement is observed in the Sibari basin ($R = 0.72$), followed by Cosenza-Ponte Europa ($R = 0.54$) and Castiglione Cosentino ($R = 0.50$). This consistency between satellite-derived and modelled relative soil moisture dynamics supports the use of ASCAT-based SM estimates to associate each observed event with the appropriate RRDB subset.

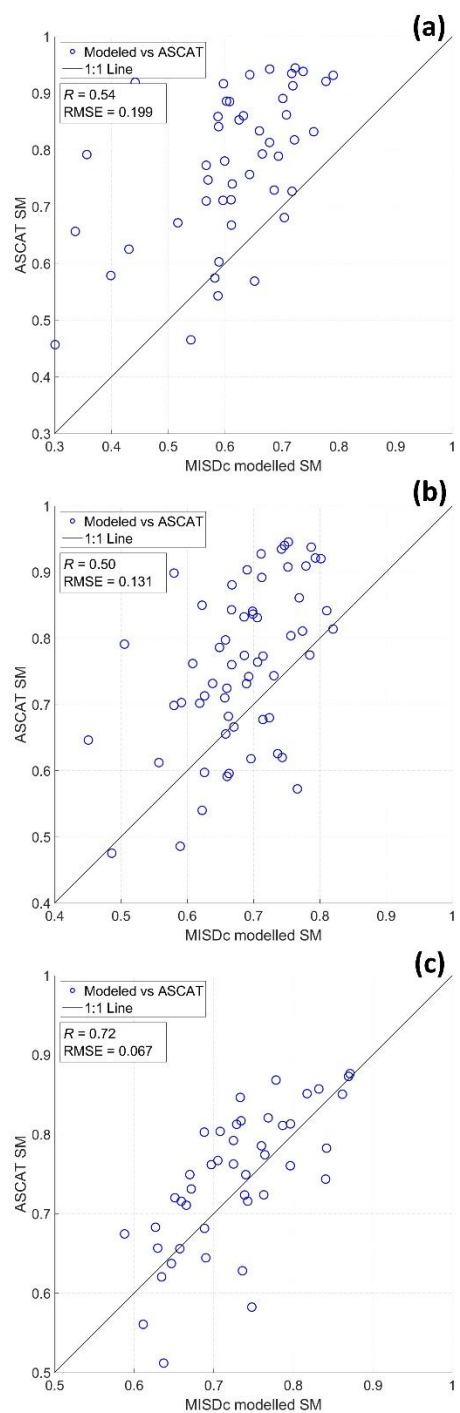


Figure 9: Comparison of the antecedent soil moisture values simulated by the MISDc model against satellite-observed ASCAT retrievals for the selected flood events. Each point represents the initial soil moisture condition assigned to an observed rainfall event, and the solid line indicates the 1:1 relationship. Panels: (a) Cosenza-Ponte Europa, (b) Castiglione Cosentino, and (c) Sibari.



The comparison between observed and simulated events is performed within a probabilistic framework. For each observed event, all RRDB simulations matching event duration and initial relative soil moisture class are extracted, and discharge percentile envelopes (5th, 25th, 50th, 75th, and 95th) are computed at each time step. These envelopes represent the range of plausible hydrological responses under equivalent forcing and antecedent conditions. Observed discharge hydrographs are then overlaid on the simulated percentile envelopes to assess the agreement between observed and simulated hydrographs. Figure 10 illustrates the validation results for events of 24, 48, and 72 h duration at the three control sections (Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari). In most cases, the observed hydrograph falls within the simulated range, indicating that the RRDB reproduces realistic runoff dynamics under varying forcing and antecedent conditions. Although detailed hydrographs are presented only for these illustrative examples, the broader set of observed events exhibits comparable behaviour.

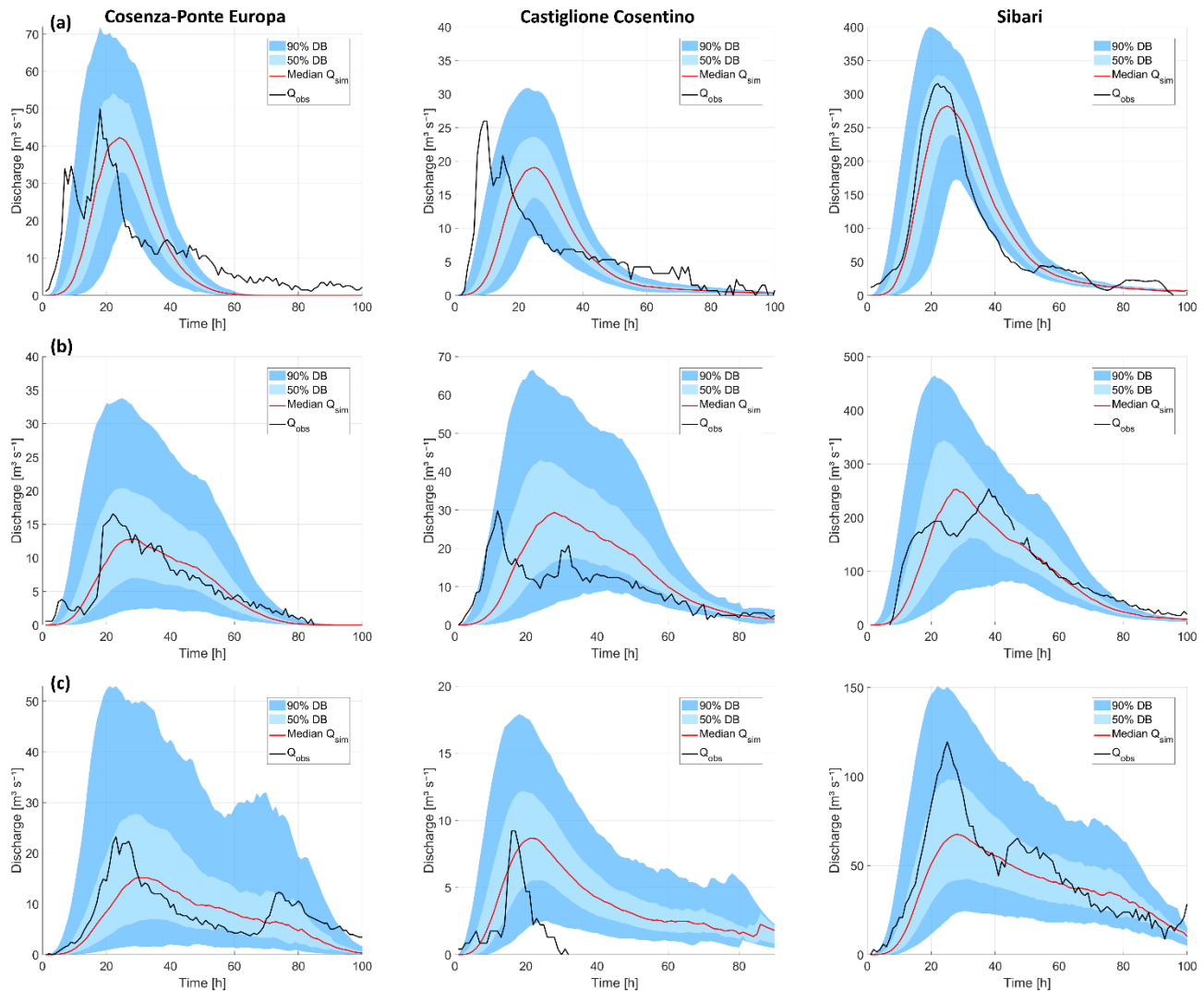


Figure 10: Validation of the RRDB against observed rainfall-runoff events with durations of 24 (a), 48 (b), and 72 (c) h at the Cosenza-Ponte Europa, Castiglione Cosentino, and Sibari control sections. Q_{obs} : observed discharge hydrograph; Median Q_{sim} : median of the RRDB-simulated discharge hydrographs; shaded bands represent the 25–75 % (50 % DB) and 5–95 % (90 % DB) ranges of the RRDB ensemble. The selected events occurred on: Cosenza-Ponte Europa: 17 January 2013 (24 h), 8 January 2019 (48 h), 29 November 2013 (72 h); Castiglione Cosentino: 17 December 2018 (24 h), 4 December 2012 (48 h), 13 February 2021 (72 h); Sibari: 13 December 2019 (24 h), 13 March 2013 (48 h), 16 February 2010 (72 h).

The comparison between observed and simulated hydrographs for all selected events is provided in Figures B1–B7 in Appendix B, which reports the results for the three control sections of Cosenza-Ponte Europa, Sibari, and Castiglione Cosentino across the different event durations considered. Observed peak flows and runoff volumes generally remain close to the variability captured by the corresponding RRDB subsets, although deviations are present for some events. In particular, the observed hydrographs do not consistently align with the median simulated response, and in some cases peak discharges exceed the upper range of the probabilistic envelope. Nevertheless, most of the observed hydrographs remain within or close



480 to the simulated distribution, indicating that the RRDB captures the overall magnitude and temporal evolution of flood events, with some underestimations of extreme peaks.

Overall, this systematic comparison confirms that RRDB provides a physically consistent representation of the rainfall-runoff behaviour of the Crati River basin. Validation against observed events supports its suitability as a tool for probabilistic flood analyses and risk assessments across different hydro-meteorological conditions.

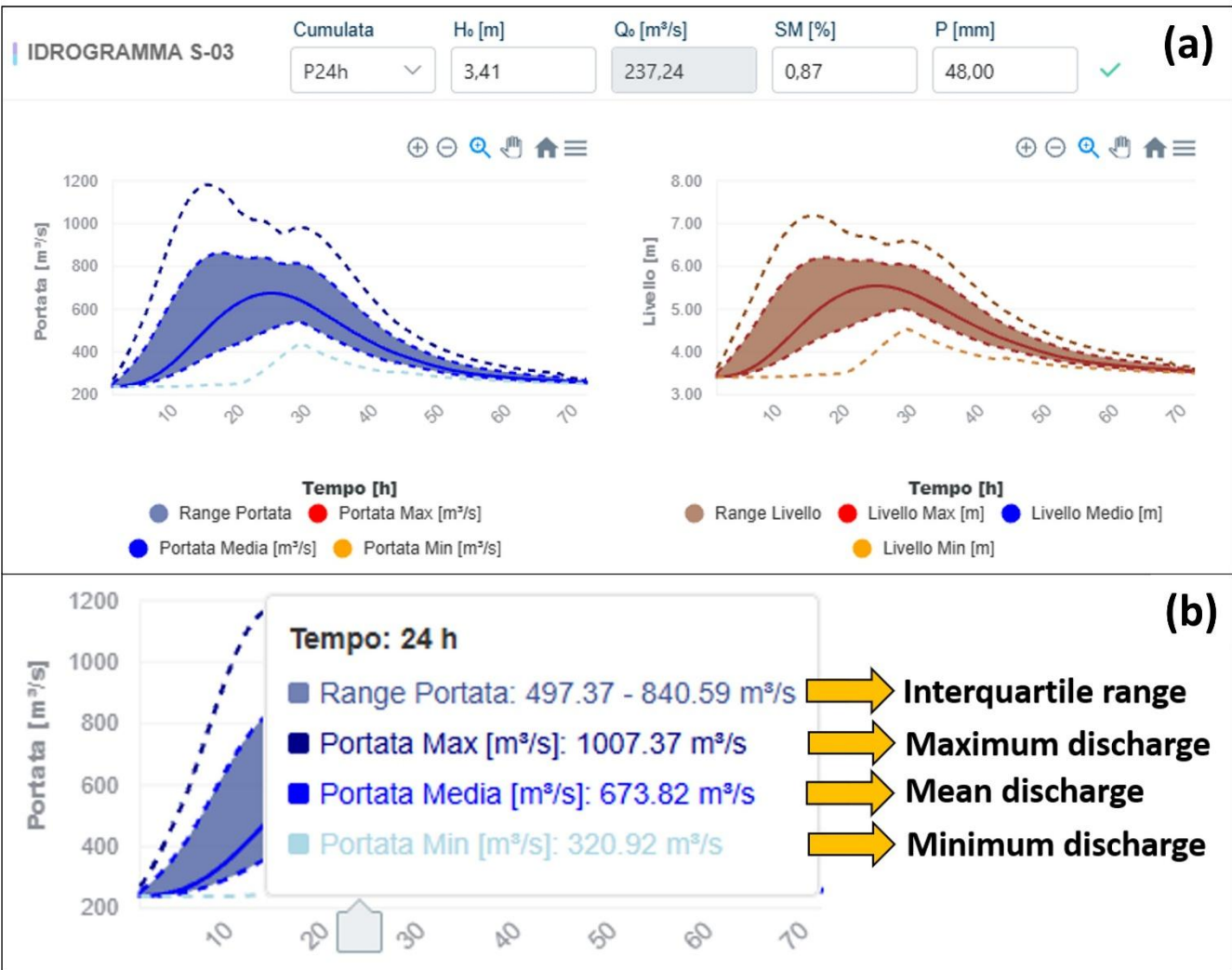
485 3.4 Operational application: integration of RRDB into the HYPES early-warning platform

The operational value of the RRDB is demonstrated through its deployment within HYPES, an operational flood forecasting platform described in detail in a dedicated study (Ruga et al., 2026), for the February 2026 flood event occurred in the Crati River basin. This real-case application evaluates the ability of the database-driven approach to support real-time probabilistic flood forecasting and deliver timely information for early-warning purposes. According to the official report provided by
 490 ARPACAL Centro Funzionale Multirischi, the event was characterized by persistent and widespread precipitation affecting the region between 11 and 20 February 2026, with cumulative rainfall locally exceeding 300 mm over the Crati basin (Bloise et al., 2026). This persistent rainfall sequence led to progressive soil saturation and multiple flood waves along the main river network. At the Sibari hydrometric section the flood peak was recorded at 17:50 on 13 February, reaching approximately 663 m³ s⁻¹, corresponding to the highest river discharge ever observed at the site. Cumulative rainfall over the 24 h preceding the
 495 peak was approximately 48 mm over the basin. Antecedent relative soil moisture conditions, reconstructed from the averaged basin-scale soil moisture derived from the ASCAT Surface Soil Moisture Climate Data Record (CDR v8 extension, 12.5 km sampling), indicated a basin-average value close to 0.87 on 12 February.

The combination of basin-average antecedent relative soil moisture and cumulative rainfall is used as a query to retrieve a set of precomputed hydrographs from the RRDB implemented within HYPES. The system extracts all synthetic hydrographs
 500 associated with similar hydrometeorological conditions, thereby producing a set of physically consistent river discharge responses. The hydrographs are then aligned with the pre-event discharge (Q_0), estimated from the observed water level (H_0) recorded 24 h before the peak, allowing a direct comparison with observed discharge conditions (see Fig. 11).

Using this information, the retrieved hydrographs define a probabilistic response distribution reflecting the high sensitivity of the Crati basin to antecedent wetness conditions, where small variations in rainfall can produce large increases in river
 505 discharge under near-saturated soils. Within this conditioned ensemble, the interquartile response domain (25th–75th percentile) ranges between approximately 497 m³ s⁻¹ and 840 m³ s⁻¹, while the expected value is 674 m³ s⁻¹.

The observed peak discharge of 663 m³ s⁻¹ lies within this interquartile range, indicating consistency with the central portion of the hydrological response distribution represented in the database. This confirms that, given the available rainfall and antecedent relative soil moisture information, the system could supply early indication of critical discharge conditions several
 510 hours before their occurrence. Figure 11 shows the corresponding predicted flood hydrographs, retrieved from the RRDB using the observed rainfall and antecedent soil moisture as input.



515 **Figure 11: HYPES full query interface. (a) Forecasted cumulative rainfall over the next 24 h (P), the antecedent soil moisture (SM), the pre-event water level (H_0) and discharge (Q_0), and the ensemble of predicted flood hydrographs. (b) Detailed view of the extracted values for the selected event. The platform interface is in Italian: portata = discharge, livello = water level, tempo = time, media = mean, max = maximum, min = minimum.**

This result shows that the integration of RRDB within HYPES can support effective early warning with information several hours before the occurrence of extreme events, supporting timely decision-making and risk mitigation actions in operational flood management. The February 2026 event illustrates two key hydrological features of the Crati basin: (i) the high sensitivity to antecedent moisture conditions, and (ii) the potential for multi-peak flood sequences generated by successive rainfall pulses. These characteristics, typical of Mediterranean environments with strong rainfall variability, underscore the need for probabilistic and process-based modelling approaches capable of accounting for both short-duration convective storms and longer synoptic-scale precipitation events.



525 4 Conclusions

In Mediterranean catchments, climate change is amplifying the occurrence of intense and unpredictable rainfall events. The inherent flash-flood exposure of many basins requires modelling tools providing reliable and timely flood predictions with simple structures and minimal input data.

In this study, a probabilistic rainfall-runoff database (RRDB) is developed for the Crati River basin in southern Italy. The
 530 RRDB integrates stochastic rainfall and air-temperature generation with hydrological modelling to provide a large ensemble of precomputed rainfall-runoff simulations spanning a broad range of event durations, rainfall amounts, and antecedent soil moisture states. By shifting the computational effort to an offline generation phase, the database enables rapid retrieval of hydrological responses during the forecasting stage while retaining the variability associated with different hydro-meteorological conditions.

535 The results support the consistency of the proposed framework from rainfall generation to hydrological response. The NSRP-IC model reproduces the main statistical and temporal characteristics of observed precipitation, including rainfall variability and extremes, while the FARIMA model preserves the seasonal structure and variability of air temperature. The MISDc model performs well at the calibrated section and reproduces the main characteristics of the observed flow regime at the independent validation sections. Comparison with ASCAT soil moisture provides additional independent support for the representation of
 540 catchment wetness dynamics and, consequently, for the characterization of antecedent conditions used in the RRDB.

The event-based validation shows that the RRDB generally encompasses the observed rainfall-runoff responses within its probabilistic range. Most observed hydrographs, peak flows, and runoff volumes fall within or close to the corresponding simulated envelopes, although deviations occur for individual events, and some extreme peak discharges are underestimated. The database therefore provides a realistic representation of the overall magnitude and temporal evolution of flood responses
 545 while accounting for the variability associated with rainfall forcing and antecedent wetness.

The integration of the RRDB into the HYPES operational forecasting platform further demonstrates its potential for real-time applications. During the February 2026 flood event, conditioning the database on observed rainfall and antecedent soil moisture rapidly provided an ensemble of physically consistent discharge hydrographs. The observed peak at Sibari falls within the interquartile range of the retrieved ensemble, showing that the database can provide an early indication of critical discharge
 550 conditions 24 h ahead of the observed peak, corresponding to the rainfall forecast window used to query the database, without requiring computationally intensive hydrological simulations during the forecasting stage. This operational assessment is based on a single event, and further testing on additional events is needed to fully establish the reliability of the approach. Nevertheless, this lead time is directly relevant for flood risk management, as it allows warnings to be issued in advance and can help reduce the impact of flood events on exposed areas.

555 Overall, the study demonstrates the potential of precomputed probabilistic rainfall-runoff databases to bridge physically based hydrological modelling and operational flood forecasting. The proposed framework is particularly relevant for catchments where computational efficiency and limited in situ observations constrain conventional forecasting approaches. Transferability

is a key strength of the framework. Its construction requires only observed rainfall and air-temperature series to calibrate the stochastic generators and the hydrological model, while its operational use relies on satellite-derived soil moisture, which is globally available and independent of ground monitoring networks. In an operational setting, rainfall forecasts (nowcasting or quantitative precipitation forecast, QPF) would replace observed rainfall to drive the retrieval of probabilistic river discharge forecasts. The approach is therefore potentially transferable to other catchments and particularly valuable in data-scarce and poorly monitored regions, where reliable flood early-warning systems are most needed yet hardest to implement, providing a practical basis for supporting stakeholders in flood-risk management and decision-making.

Appendix A

Tables A1–A3 present the complete event-based datasets for the three control sections: Sibari (Table A1), Cosenza-Ponte Europa (Table A2), and Castiglione Cosentino (Table A3). For each rainfall event, the tables include the event start date, event duration, and areal cumulative rainfall over the corresponding contributing sub-basin, together with antecedent soil moisture conditions derived from both the MISDc hydrological model and ASCAT satellite observations. The datasets provide the basis for the statistical analyses and model evaluation presented in the main text. Dates are given as dd/mm/yyyy.

Table A1: Event-based dataset for the Sibari control section. For each rainfall event, the table reports event start date, event duration, areal cumulative rainfall over the corresponding sub-basin, and antecedent soil moisture conditions derived from both MISDc simulations and ASCAT satellite observations.

Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
01/01/2010	63	34.47	0.67	0.73
09/01/2010	96	47.72	0.66	0.72
30/01/2010	65	61.90	0.73	0.82
06/02/2010	58	37.27	0.69	0.64
10/02/2010	54	52.96	0.71	0.77
16/02/2010	69	30.20	0.72	0.76
09/03/2010	39	50.23	0.74	0.63
18/10/2010	40	54.58	0.75	0.58
24/12/2010	43	46.71	0.67	0.71
28/02/2011	35	61.37	0.64	0.51
21/02/2012	64	55.65	0.63	0.66
13/04/2012	49	71.17	0.61	0.56
17/01/2013	32	56.42	0.87	0.87
21/01/2013	47	20.81	0.73	0.81
24/01/2013	41	40.04	0.74	0.75
13/03/2013	53	45.26	0.84	0.74
25/03/2013	89	38.03	0.65	0.64



Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
15/11/2013	28	40.94	0.69	0.80
30/11/2013	45	51.77	0.67	0.75
03/12/2013	35	21.83	0.77	0.82
20/01/2014	48	46.75	0.73	0.85
03/02/2014	36	14.69	0.78	0.87
28/12/2014	34	67.88	0.59	0.67
29/01/2015	55	72.61	0.74	0.72
02/02/2015	27	10.65	0.84	0.78
05/02/2015	63	36.49	0.76	0.79
26/11/2015	31	29.71	0.80	0.81
23/02/2018	35	31.05	0.72	0.79
27/11/2018	28	28.87	0.87	0.88
08/01/2019	66	64.29	0.61	0.48
04/02/2019	45	22.20	0.69	0.68
24/11/2019	34	55.12	0.63	0.68
13/12/2019	29	37.97	0.76	0.77
21/12/2019	61	87.73	0.71	0.80
08/12/2020	41	42.04	0.80	0.76
24/01/2021	30	40.97	0.83	0.86
31/01/2021	75	39.81	0.70	0.76
10/02/2021	32	30.25	0.79	0.81
13/02/2021	66	15.05	0.74	0.72
19/03/2021	62	57.42	0.63	0.62
28/11/2021	39	43.68	0.82	0.85
10/12/2021	33	36.61	0.86	0.85
22/11/2022	38	47.31	0.76	0.72
29/11/2022	38	41.78	0.66	0.66
10/12/2022	35	44.16	0.65	0.72

575 **Table A2: Event-based dataset for the Cosenza-Ponte Europa control section. For each rainfall event, the table reports event start date, event duration, areal cumulative rainfall over the corresponding sub-basin, and antecedent soil moisture conditions derived from both MISDc simulations and ASCAT satellite observations.**

Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
26/01/2010	38	28.89	0.61	0.74
31/01/2010	25	29.59	0.78	0.92
06/02/2010	31	23.05	0.70	0.68



Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
10/02/2010	25	31.38	0.72	0.82
14/02/2010	52	23.02	0.72	0.73
16/02/2010	61	33.84	0.69	0.73
24/02/2010	38	14.43	0.64	0.93
09/03/2010	34	53.27	0.60	0.89
18/10/2010	31	61.83	0.43	0.63
24/12/2010	37	52.14	0.57	0.75
28/02/2011	30	63.25	0.59	0.54
04/12/2011	61	55.41	0.36	0.79
13/04/2012	43	90.06	0.34	0.66
04/12/2012	43	51.15	0.58	0.57
17/01/2013	29	49.85	0.74	0.94
22/01/2013	22	10.10	0.70	0.89
24/01/2013	35	37.87	0.67	0.79
14/03/2013	21	25.04	0.72	0.91
26/03/2013	25	24.67	0.64	0.76
02/04/2013	28	16.09	0.60	0.92
29/11/2013	62	64.25	0.65	0.57
20/01/2014	52	48.70	0.59	0.84
01/02/2014	35	37.21	0.63	0.86
27/03/2014	30	19.96	0.66	0.83
28/12/2014	30	77.93	0.40	0.58
31/01/2015	33	43.32	0.79	0.93
05/02/2015	53	44.01	0.68	0.81
21/10/2015	32	76.26	0.30	0.46
11/11/2016	44	47.60	0.44	0.92
22/01/2017	35	30.40	0.57	0.71
12/02/2018	42	45.60	0.52	0.67
23/02/2018	30	36.28	0.62	0.85
04/11/2018	24	38.50	0.61	0.71
27/11/2018	23	42.10	0.72	0.93
17/12/2018	25	34.97	0.57	0.77
08/01/2019	44	68.38	0.54	0.47
13/11/2019	21	22.22	0.76	0.83
23/11/2019	31	59.71	0.59	0.60
12/12/2019	51	59.42	0.60	0.71



Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
21/12/2019	61	89.20	0.59	0.86
05/12/2020	38	51.27	0.61	0.67
24/01/2021	33	48.28	0.69	0.79
02/02/2021	26	11.74	0.68	0.94
10/02/2021	26	40.70	0.61	0.89
28/11/2021	41	57.90	0.71	0.86
10/12/2021	31	43.51	0.72	0.94
10/12/2022	28	54.06	0.60	0.78

580 **Table A3. Event-based dataset for the Castiglione Cosentino control section. For each rainfall event, the table reports event start date, event duration, areal cumulative rainfall over the corresponding sub-basin, and antecedent soil moisture conditions derived from both MISDc simulations and ASCAT satellite observations.**

Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
26/01/2010	41	33.17	0.62	0.70
31/01/2010	27	29.80	0.79	0.92
06/02/2010	38	26.90	0.72	0.68
10/02/2010	29	33.65	0.77	0.81
14/02/2010	55	24.33	0.73	0.74
16/02/2010	86	38.04	0.69	0.73
24/02/2010	56	16.91	0.71	0.93
04/03/2010	48	33.50	0.58	0.70
09/03/2010	37	56.45	0.66	0.80
18/10/2010	33	63.77	0.74	0.63
24/12/2010	42	55.47	0.63	0.71
28/02/2011	31	68.41	0.62	0.54
04/12/2011	63	60.54	0.51	0.79
13/04/2012	44	92.63	0.45	0.65
04/12/2012	45	54.78	0.70	0.62
17/01/2013	31	53.37	0.75	0.94
22/01/2013	23	11.65	0.71	0.89
24/01/2013	38	40.49	0.69	0.77
12/02/2013	38	20.80	0.77	0.57
14/03/2013	24	27.34	0.78	0.91
18/03/2013	39	20.45	0.69	0.74
26/03/2013	33	28.33	0.71	0.76
02/04/2013	32	19.91	0.69	0.90



Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
29/11/2013	63	64.28	0.66	0.59
20/01/2014	54	51.73	0.70	0.84
24/01/2014	35	30.34	0.71	0.77
01/02/2014	38	40.80	0.70	0.84
27/03/2014	32	22.81	0.71	0.83
28/12/2014	32	80.25	0.56	0.61
31/01/2015	34	47.06	0.79	0.94
04/02/2015	32	14.14	0.71	0.68
05/02/2015	56	45.80	0.69	0.83
21/10/2015	35	77.42	0.49	0.48
27/11/2015	19	9.39	0.75	0.91
10/11/2016	46	48.61	0.58	0.90
22/01/2017	37	35.03	0.59	0.70
12/02/2018	41	47.78	0.64	0.73
23/02/2018	31	37.54	0.67	0.84
26/02/2018	40	19.91	0.74	0.62
04/11/2018	25	39.82	0.66	0.72
27/11/2018	25	47.48	0.80	0.92
17/12/2018	27	35.34	0.65	0.79
08/01/2019	50	73.30	0.59	0.49
29/01/2019	58	38.31	0.66	0.60
04/02/2019	42	34.57	0.66	0.68
13/11/2019	22	23.54	0.81	0.84
24/11/2019	32	62.40	0.63	0.60
12/12/2019	52	63.63	0.66	0.71
21/12/2019	63	91.32	0.62	0.85
05/12/2020	43	54.67	0.66	0.66
09/12/2020	36	41.87	0.82	0.81
24/01/2021	34	50.54	0.76	0.80
01/02/2021	30	12.56	0.74	0.93
10/02/2021	27	41.86	0.67	0.88
13/02/2021	70	17.88	0.67	0.76
28/11/2021	43	60.62	0.77	0.86
10/12/2021	33	44.41	0.75	0.95
22/11/2022	35	52.67	0.78	0.77
30/11/2022	25	50.73	0.67	0.67



Event start date	Duration (h)	Cumulative rainfall (mm)	MISDc SM initial	ASCAT SM
10/12/2022	31	57.46	0.61	0.76

Appendix B

Figures B1–B7 show the comparison between observed and RRDB-simulated discharge hydrographs for all the selected events at the three control sections and for the different event durations considered. In each panel, the observed hydrograph is overlaid on the percentile envelopes retrieved from the RRDB for the corresponding event duration and antecedent soil moisture class, as described in Sect. 3.3.

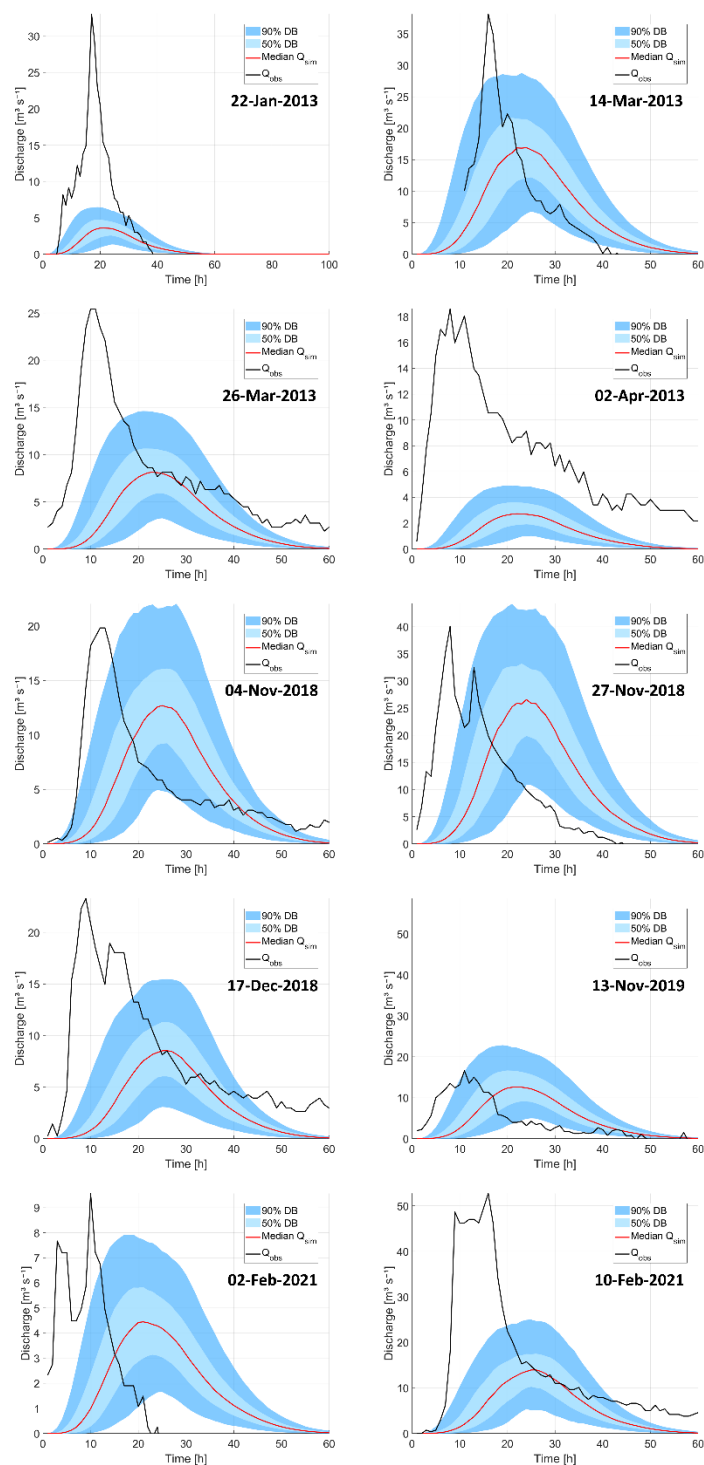


Figure B1: Observed and RRDB-simulated discharge hydrographs for 24 h rainfall events at the Cosenza-Ponte Europa hydrometric section.

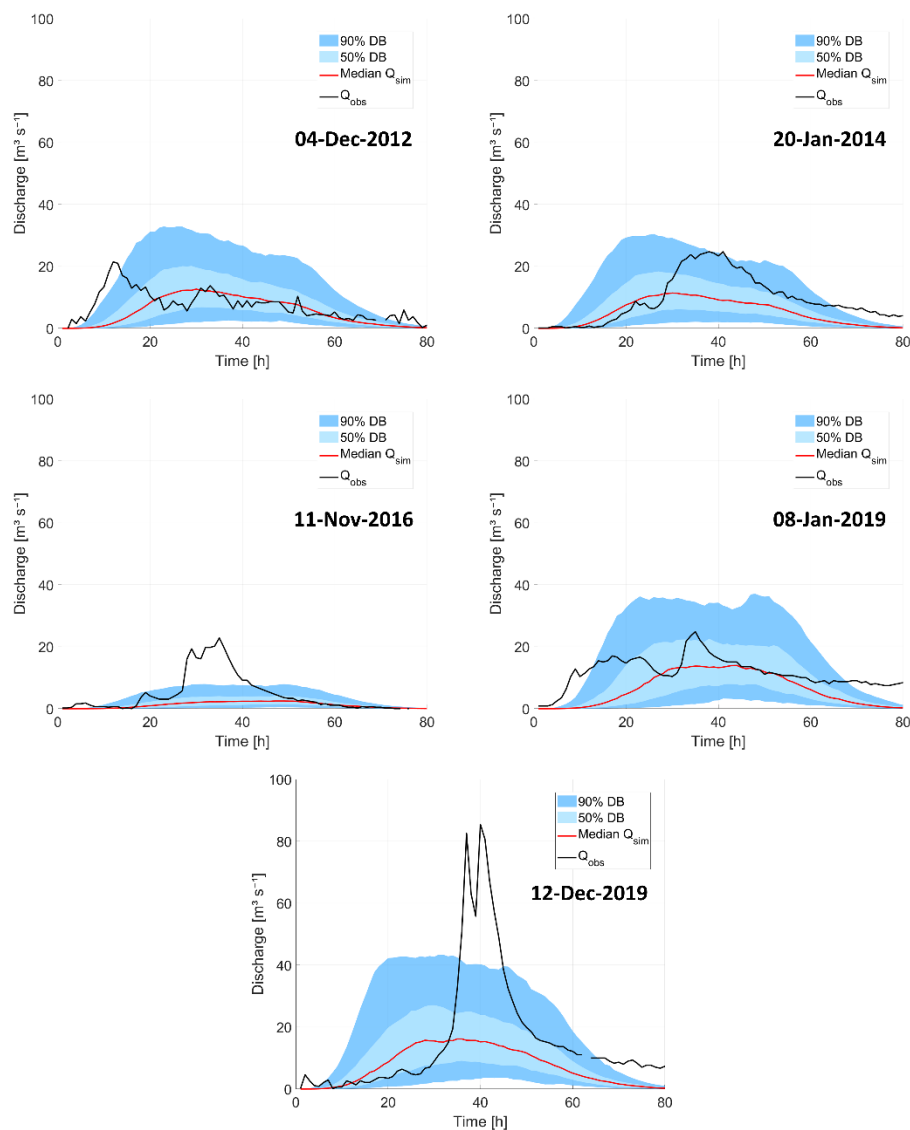
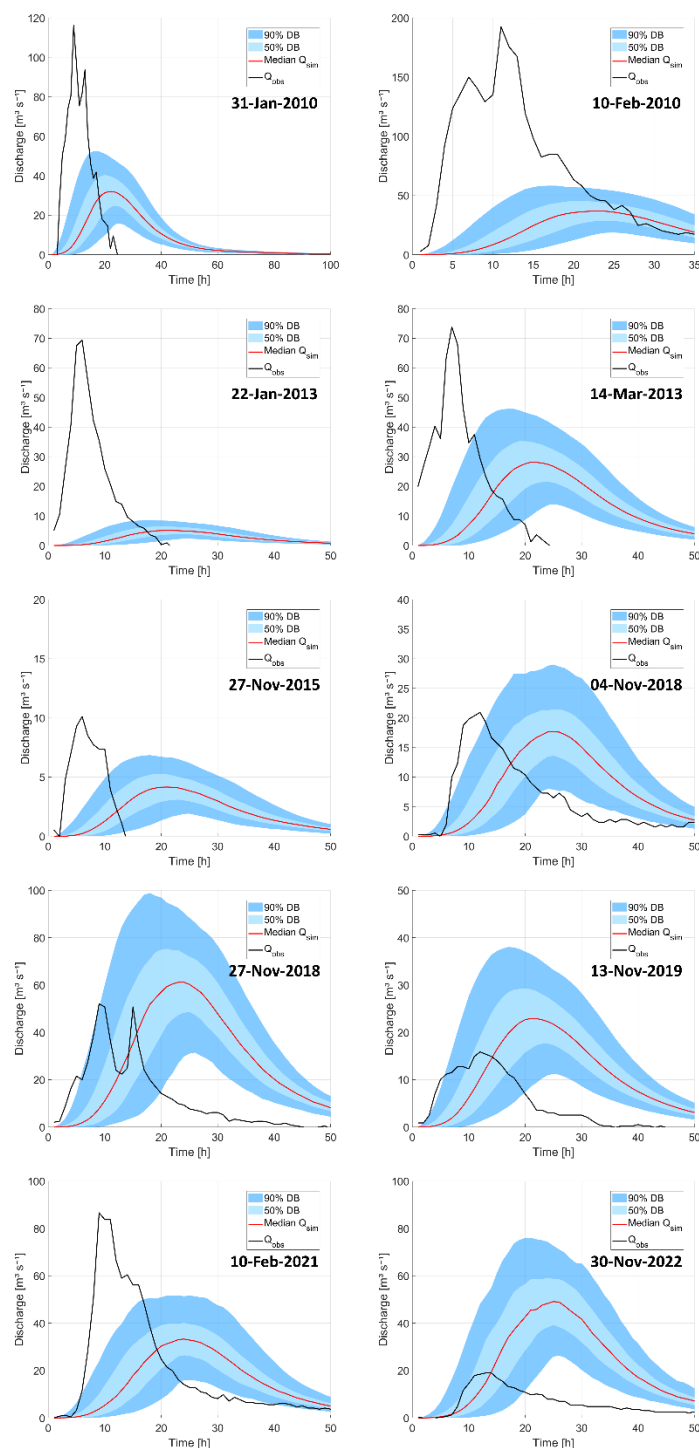


Figure B2: Observed and RRDB-simulated discharge hydrographs for 48 h rainfall events at the Cosenza-Ponte Europa hydrometric section.



595 **Figure B3: Observed and RRDB-simulated discharge hydrographs for 24 h rainfall events at the Castiglione Cosentino hydrometric section.**

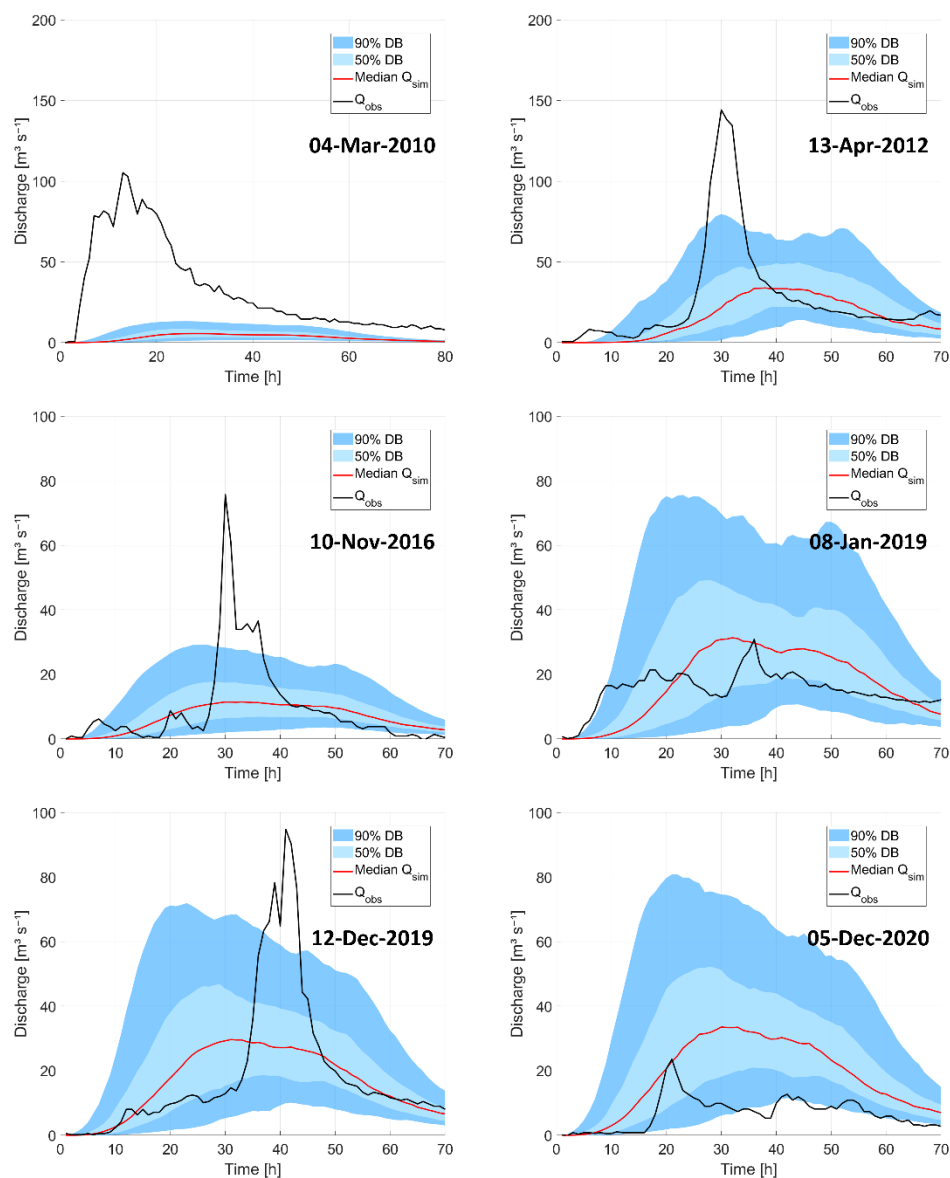


Figure B4: Observed and RRDB-simulated discharge hydrographs for 48 h rainfall events at the Castiglione Cosentino hydrometric section.

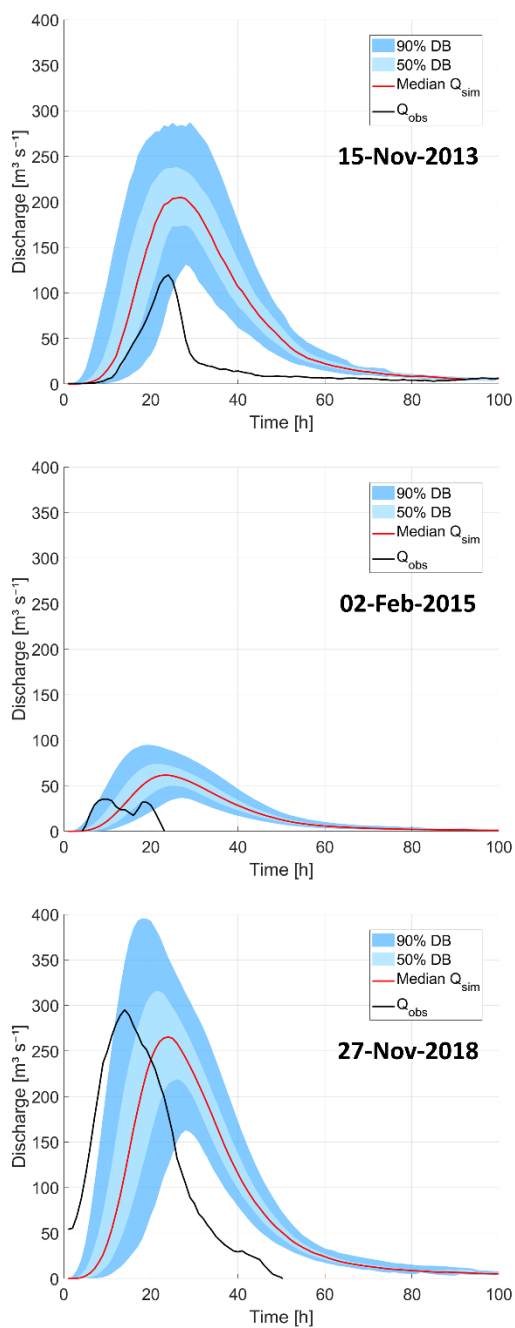


Figure B5: Observed and RRDB-simulated discharge hydrographs for 24 h rainfall events at the Sibari hydrometric section.

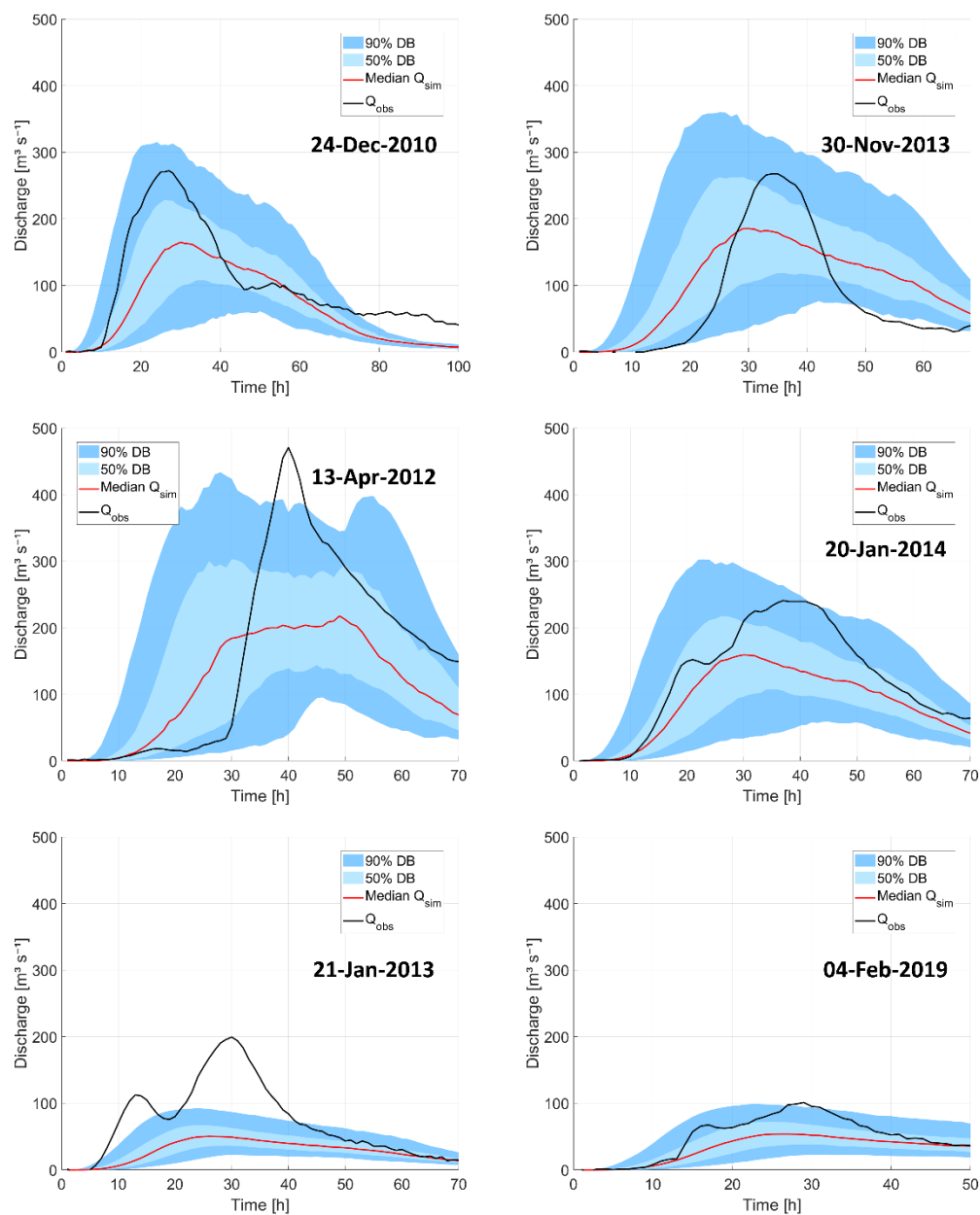
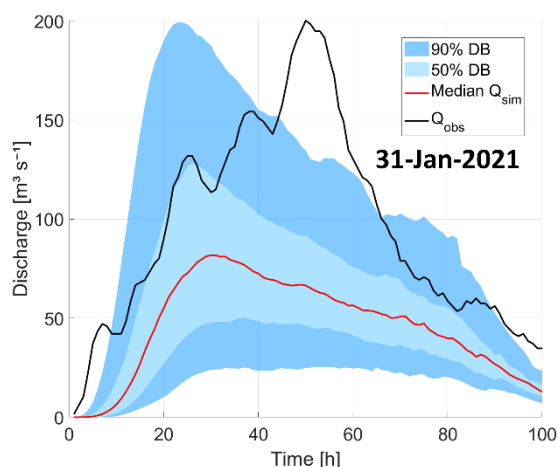


Figure B6: Observed and RRDB-simulated discharge hydrographs for 48 h rainfall events at the Sibari hydrometric section.



605 **Figure B7: Observed and RRDB-simulated discharge hydrographs for 72 h rainfall events at the Sibari hydrometric section.**

Code and data availability

The gridded precipitation and air temperature data for Italy were produced by CIMA Research Foundation and are available upon request to CIMA (Bruno et al., 2021; Avanzi et al., 2023). ASCAT surface soil moisture data (H121) are distributed by the EUMETSAT H SAF programme (Wagner et al., 2013). Water level and discharge records at Sibari, Castiglione Cosentino and Cosenza-Ponte Europa were provided by ARPACAL – Centro Funzionale Multirischi and are available upon request to the data owner. The event-based datasets underlying the analyses are reported in Appendix A. The synthetic hydro-meteorological series, the rainfall-runoff database and the codes used for the stochastic generation and the hydrological simulations are available from the corresponding author upon request.

Author contributions

615 MD: conceptualization, data curation, formal analysis, investigation, methodology, resources, software, validation, visualization, writing (original draft preparation), writing (review and editing).

TM: conceptualization, funding acquisition, methodology, project administration, writing (review and editing).

DDS: data curation, formal analysis, investigation, resources, software, writing (review and editing).

620 CM: conceptualization, methodology, project administration, supervision, writing (original draft preparation), writing (review and editing).

SB: writing (original draft preparation), writing (review and editing).

SC: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing (original draft preparation), writing (review and editing).



Competing interests

625 The authors declare that they have no conflict of interest.

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635 Technologies for climate change adaptation and quality of life improvement, no. ECS0000009.

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