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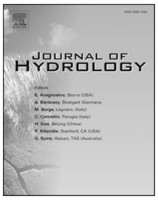

Research papers

Continuous hydrologic modelling for design simulation in small and ungauged basins: A step forward and some tests for its practical use

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ABSTRACT

The design hydrograph estimation in small and ungauged basins represents one of the most common practices and, yet, a challenging open research topic for hydrologists. When discharge observations are not available, the practitioner is compelled to apply empirical approaches. The rational formula is slowly disappearing, while event-based approaches are more and more widespread. A step forward is represented by continuous models that have the potential to address the major drawbacks of event-based approaches. In this work we applied a continuous model specifically designed for ungauged basins (COSMO4SUB) and tested its use in conditions where typically the rational formula and the event-based approaches are applied. Results confirm that the continuous modelling is suitable for rapid and effective design simulations supporting flood hazard modelling and mapping studies.

1. Introduction

Prediction in small and ungauged basins is an evergreen topic in hydrology. The understanding, simulation and mitigation of flooding scenarios in watersheds characterized by limited contributing areas represent an open challenge for researchers and floodplain managers. Raising impacts of flash floods are prompting hydrological sciences to find viable modelling approaches in order to tackle the lack of discharge observations and the impossibility of adopting early warning systems, a critical gap especially for small-scale basins (Barredo, 2007; Marchi et al., 2010). Several studies emphasized the importance of proper knowledge of flood wave generation and dynamics in upstream basins and tributaries (Allamano et al., 2009; Convertino et al., 2019; McGlynn et al., 2013; Peña and Nardi, 2018; Petroselli et al., 2019, 2020a, 2020b).

Since the inception of the Prediction in Ungauged Basins (PUB) decade by the International Association of Hydrological Sciences (2003–2012; Sivapalan et al., 2003; Blöschl et al., 2013; Hrachowitz et al., 2013) to most recent IAHS Panta Rhei effort fostering crucial stimuli to address most pressing social challenges linked to hydro-extremes (Montanari et al., 2013), the meaning of the term ungauged has changed. Recent advancements of remote sensing technologies providing a new generation of large scale topographic and hydrologic observations are suggesting to redefine the meaning of the original desperate ungauged definition.

Digital elevation and terrain models are nowadays freely available for the entire globe supporting topographic, land and human feature characterization at adequate resolution for hydrologic studies (e.g. Yamazaki et al., 2017; Melchiorri et al., 2018). Rainfall observations are increasingly available at different spatial and time scales with length of precipitation records reaching a multiple decade length (Sun et al., 2018), considering the attention and financial support received since the 80s. While recent budget reduction and decreased interest in ground base precipitation monitoring, in favor of remote sensing (Berne et al., 2004; Paz et al., 2020), are posing challenges for many regions of the worlds that are lagging behind for the lack of adequate financing and

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implementation of ground hydrologic observations (Jenkins et al., 2020), we posit here that the concept of ungauged shall be mainly linked to runoff processes. We define ungauged those basins completely or partially lacking of hydrometric observations and, consequently, unable to support calibration procedures for elaborate hydrological modelling. In practical terms, ungauged basins represent case studies where practitioners are forced to use empirical approaches for the lack of flow discharge and hydrograph series data and frequency analyses.

The rational formula represented the most popular approach for rainfall-runoff modelling due to its simplicity and to the limited watershed input information needed for its application. Digital topography and computer power advancements fostered the development of ungauged basin rainfall-runoff models, paving the way for effective employment of event-based approach in place of the rational formula (Viglione and Blöschl, 2009; Castiglioni et al., 2010; Blöschl et al., 2013; Haberlandt and Radtke, 2014; Sene, 2012). Such improvements allowed to mitigate some crucial drawbacks of rational formula, providing more accurate results while reducing the chronic uncertainty of empirical procedures. As emphasized in Grimaldi and Petroselli (2015), event-based approaches reduce the subjectivity of empirical procedures relaxing the flood analyst assumptions and diminishing the major uncertainty components affecting hydrologic modelling parametrizations.

A further pivotal scientific advancement was represented by statistical climate and weather modelling whose spatial and temporal scale, accuracy and effectiveness grow considerably in the last decade. Indeed, statistical methods for rainfall simulation rapidly evolved making available a variety of approaches and models that are able to generate any kind of synthetic scenarios (just to mention some examples: Koutsoyiannis et al., 2003; Kossieris et al., 2018; Müller and Haberlandt, 2018; Papalexiou, 2018; Toulemonde et al., 2020). This represents an additional crucial outcome, potentially helpful for the hydrologic modelling in ungauged basins. Rainfall observations (daily, sub-daily, maximum annual values for different durations) and time series generations are available for as fundamental input for continuous models. Data availability and science advancements stimulated a variety of investigations on continuous frameworks for hydrological applications (Ormsbee, 1989; Blazkova and Beven, 2002; Chu and Steinman, 2009; Camici et al, 2011; Pathiraja et al, 2012; Breinl, 2016; Lamb et al., 2016; Blazkova et al, 2017; Davtalab et al., 2017; Rowe and Smithers, 2018; Winter et al, 2019). It is our opinion that continuous model evolution is mature enough to support its development for ungauged basins (Boughton and Droop, 2003).

Apparently, it could be a contradiction to adopt a more complex approach for case studies without sufficient observations for calibration. Continuous hydrologic modelling are not more parameter parsimonious or less complex than event-based approaches. However, the added value of continuous approach is significant in term of mitigating artefacts linked to synthetic and subjective characterization of design hydrograph attributes (Grimaldi et al., 2012b; Rogger et al, 2012; Falter et al., 2015; Okoli et al, 2019; Berthet et al, 2009; Fleischmann et al, 2019; Winter et al, 2019). We posit that the leap forward observed in the replacement of the rational formula with event-based approaches is analogously developing for the transition from event-based towards continuous modelling. In practice, the benefit would be to have a more realistic estimation of hydrograph volume and duration, to remove some modules of the event-based approach (i.e. design hyetograph, Intensity-Duration-Frequency - IDF - curves), and to have available a *design simulation,* that consists in a long runoff time series useful for a variety of applications, crucial also for small basins.

This work is based on the application of the COntinuous Simulation Model for Small Ungauged Basins, namely COSMO4SUB (Grimaldi et al. 2012a). In this work a step forward for COSMO4SUB model is proposed

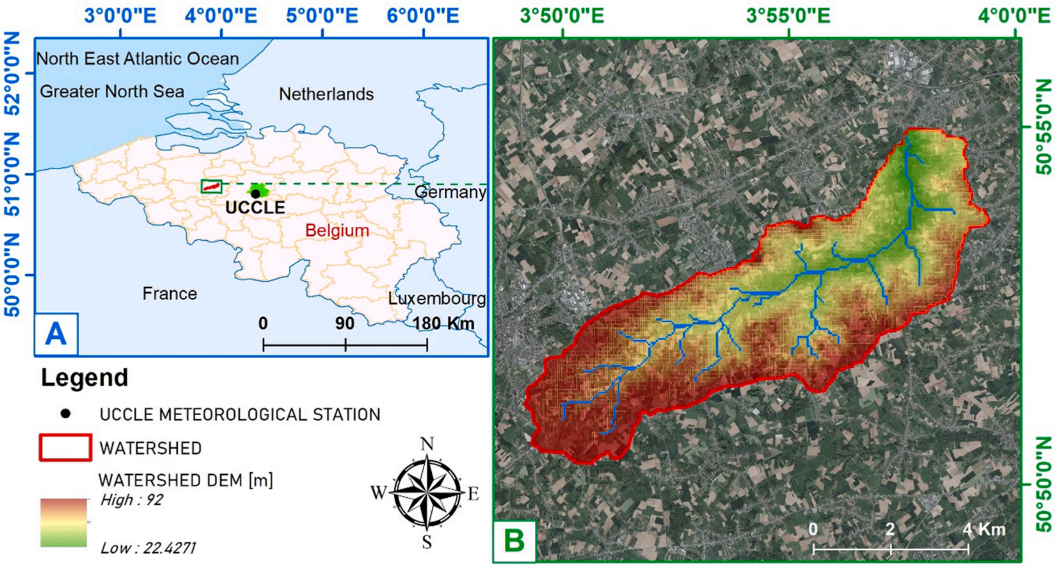

Fig. 1. Case study description. A) geographical identification of the Mere watershed and the UCCLE raingauge; B) DEM and drainage network extracted with 0.5 km^2 contributing area threshold.

Table 1

UCCLE time series summary. Dry lag frequency, average precipitation ($\bar{h}$), standard deviation (σ) and quantiles ($q_{0\%}$,.., $q_{100\%}$) for the entire rainfall time series at different time resolutions (10 min – 10 h – 1 year) and for the sample of maxima annual values for 10-hour duration.

Sample and scale	Dry lag frequency [%]	$\bar{h}$ [mm]	σ [mm]	$q_{0\%}$ [mm]	$q_{20\%}$ [mm]	$q_{50\%}$ [mm]	$q_{80\%}$ [mm]	$q_{90\%}$ [mm]	$q_{100\%}$ [mm]
Full time series [10 min]	94.0	0.255	0.001	0.1	0.1	0.1	0.3	0.5	19.6
Full time series [10 h]	63.5	2.521	0.019	0.1	0.3	1.2	4	6.5	55
Full time series [1 year]	–	805.3	129.1	412.7	699	813.5	916.5	958	1085
Annual maxima [10 h]	–	27.5	9.2	13.1	19.4	25.9	32.1	41	55

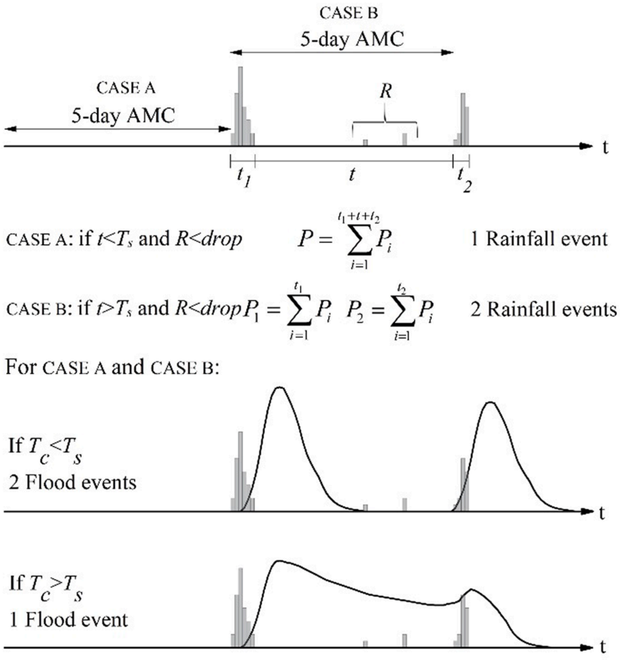

Fig. 2. *Ts* and *drop* parameter description. *t* is the duration between two storms, *R* is a possible amount of rainfall intra-events, *P* and P_i are gross rainfall amounts. In "Case A" the duration between two different storms is less of *Ts* and consequently a single rainfall event is identified. Vice versa "Case B" provides two separated events. For both cases the flood events are conditioned by the Tc and the unit hydrograph convolution.

and tested to verify its practical use. Compared to the original COSMO4SUB contribution, here, the procedure is tested applying the rainfall-runoff transformation on observed long rainfall time series that allows a more realistic evaluation of the continuous framework. Moreover, the excess rainfall estimation is performed implementing the CN4GA (Curve Number for Green-Ampt) method (Grimaldi et al., 2013a, 2013b) that substitutes the standard NRCS-CN (National Resources Conservation Service – Curve Number) method included in the original version of COSMO4SUB. In this work the model accuracy, obtained comparing observed and simulated discharges is not provided, since already verified in a previous work (Grimaldi et al. 2012a), while, sensitivity analyses on separation time, extreme event selection, hydrograph identification, and computational time are implemented benefiting from the use of an observed rainfall time series.

2. Data and materials

The rainfall time series at 10-min resolution (Tu Pham et al. 2018) is employed, being one the longest and consistent series available to date at global scale. The time series consists of 105 years of rainfall observations, from 1 January 1898 to 31 December 2002, measured by a Hellmann-Fuess pluviograph in the climatological park of the Royal Meteorological Institute at UCCLE (see Fig. 1a), near Brussels, Belgium (Demarée, 2003). The recorded rainfall data have a constant high quality over the observation-period because data has been recorded, since 1898, by the same measuring instrument, at the same location, and adopting the same data processing method (Ntegeka and Willems, 2008).

This time series is particularly useful for investigating on model parameters related to inter-event rainfall properties that could not be well reproduced by synthetic rainfall scenarios. Indeed, it is useful to verify if the trivial rainfall spikes or natural intermittency could affect the separation time parameters or the output hydrograph selection (definition and details will be available in Section 3). A brief overview of the UCCLE rainfall time series is provided in Table 1.

Table 2
"Basic" configuration of COSMO4SUB parameters assigned and derived from the specific case study information described in section 2.

Parameter	Description	Value	Unit
Δt	Time interval (observed rainfall time series resolution)	10	min
CN	Curve Number (associated to land use and soil type class B)	64.4	–
λ	Initial abstraction ratio (default value NRCS-CN procedure)	0.2	–
T_S	Separation Time	24	hours
drop	Amount of rainfall observed within Ts	0.1	mm
Q_{INIT}	Hydrograph selection method: discharge value when the hydrograph begins	0	m^3/s
Q_{END}	Hydrograph selection method: discharge value when the hydrograph ends	0.01	m^3/s
T_c	Concentration Time	9.8	hours
A_T	Contributing area threshold for discriminating channel and hillslope cells	0.5	km^2

A small watershed located in proximity to the UCCLE raingauge is selected as case study (see Fig. 1a). It pertains to the catchment of the Molenbeek river, tributary of Deender river, located in west part of Brussels, in a region delimited by the villages of Erpe-Mere (North-East corner) and Zottegem (South-West corner). The watershed is identified by the outlet cross-section of Mere with a total contributing area of 41.1 km^2. The Digital Elevation Model (DEM) was gathered from the Copernicus Land Monitoring Service - EU-DEM and resampled at 50 m resolution. As shown in Fig. 1b, the selected domain of study is characterized by a long and narrow shape. It is located in a flat area with an elevation range 22–92 m a.s.l. and an average slope 2.9%. The simulated drainage network is estimated using 0.5 km^2 as contributing area threshold (A_T). The watershed concentration time (T_c) is estimated to be approximately 9.8 h (NRCS, 1997).

The watershed pertains to a region with mainly loamy soils and a gentle rolling landscape. The soils have different drainage conditions ranging from dry to medium wet, and profile development ranging from poorly to strongly differentiated horizons. The soil moisture storage capacity is limited, so the river has large discharge fluctuations. The baseflow discharges are small, while the response to rainfall is significant. It is noteworthy that in the selected cross section, measurement of hourly discharge is available from 1986. The mean and maximum flows can be estimated as 0.45 m^3/s and approximately 10 m^3/s, respectively.

Table 3
Hydrograph selection methods compared in the Test 3. Acronyms are included as labels in Fig. 5. *Dry* scenarios refer to the sum of discharge observed in consecutive lags.

Hydrograph selection method - Scenarios	Hydrograph starting point	Hydrograph ending point
Scenario 1 - Acronym: Q03	$Q_{INIT} \geq 0.3\ m^3/s$	$Q_{END} \leq 0.3\ m^3/s$
Scenario 2 - Acronym: Q025	$Q_{INIT} \geq 0.25\ m^3/s$	$Q_{END} \leq 0.25\ m^3/s$
Scenario 3 - Acronym: Q02	$Q_{INIT} \geq 0.2\ m^3/s$	$Q_{END} \leq 0.2\ m^3/s$
Scenario 4 - Acronym: Q015	$Q_{INIT} \geq 0.15\ m^3/s$	$Q_{END} \leq 0.15\ m^3/s$
Scenario 5 - Acronym: Q01	$Q_{INIT} \geq 0.1\ m^3/s$	$Q_{END} \leq 0.1\ m^3/s$
Scenario 6 - Acronym: Q005	$Q_{INIT} \geq 0.05\ m^3/s$	$Q_{END} \leq 0.05\ m^3/s$
Scenario 7 - Acronym: Q0	$Q_{INIT} \geq 0.001\ m^3/s$	$Q_{END} \leq 0.001\ m^3/s$
Scenario 8 - Acronym: Dry2	$Q_{INIT} \geq 0.001\ m^3/s$	Q_{END}: $\sum_{i=1}^{2} Q_i \leq 0.001\ m^3/s$
Scenario 9 - Acronym: Dry3	$Q_{INIT} \geq 0.001\ m^3/s$	Q_{END}: $\sum_{i=1}^{3} Q_i \leq 0.001\ m^3/s$
Scenario 10 - Acronym: Dry4	$Q_{INIT} \geq 0.001\ m^3/s$	Q_{END}: $\sum_{i=1}^{4} Q_i \leq 0.001\ m^3/s$
Scenario 11 - Acronym: Dry5	$Q_{INIT} \geq 0.001\ m^3/s$	Q_{END}: $\sum_{i=1}^{5} Q_i \leq 0.001\ m^3/s$
Scenario 12 - Acronym: Dry6	$Q_{INIT} \geq 0.001\ m^3/s$	Q_{END}: $\sum_{i=1}^{6} Q_i \leq 0.001\ m^3/s$

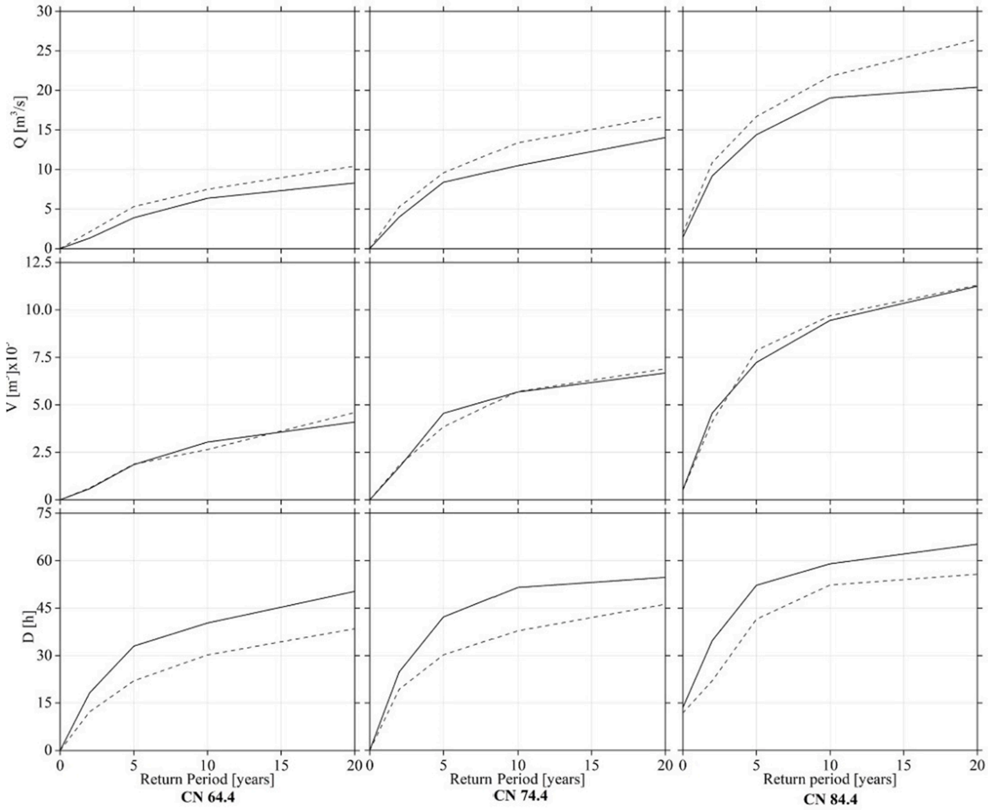

Fig. 3. Comparison between NRCS-CN (continuous black lines) and CN4GA methods (dashed lines) in estimating the annual maximum values of Q (first row), V (second row), and D (third row) using Q as driving variable. Columns are related to different curve numbers. The Q, V, D values are compared through empirical return periods.

The land cover was classified by means of the CORINE Land Cover database (at level III and related to the year 2018). The upstream watershed area is mainly rural, while the downstream part is more urbanized. Agricultural activities in the catchment account for the 76% of the total area. The NRCS Curve Number value, equal to 64.4, was quantified through empirical evaluation using look-up tables (NRCS, 2008). For a more detailed characterization of the catchment, see El-Sadek (2007) and Willems (2014).

3. COSMO4SUB modelling approach

A detailed description of Continuous Simulation Model For Small and Ungauged Basin (COSMO4SUB) is available in Grimaldi et al. (2012a) while here a brief description is reported focusing on the modules that have been the subject of novel updates. The COSMO4SUB approach is characterized by four steps: 1) the rainfall scenario simulation; 2) the excess rainfall estimation; 3) the excess rainfall-runoff transformation; 4) the design simulation strategy.

The first step of COSMO4SUB model is the rainfall scenario simulation. Starting from raingauge data series, a long sub-hourly rainfall time series is generated. 500 or 1000 years at 10-15 min of resolution represent ideal model input. In the original COSMO4SUB work, a mixed copula-based simulator and a continuous-in-scale universal multifractal approach were employed. Noting that the identification of the appropriate rainfall generator is a crucial step, considering a wide variety of options are available in literature (Caldwell et al., 2009; Kossieris et al., 2018; Callau Poduje and Haberlandt, 2017; Kim et al., 2017; Pohle et al, 2018; Li et al, 2018; Verdin et al., 2019; Zhao et al., 2019; Zhou et al., 2020), a specific study for investigating which rainfall generator model would be the optimal candidate for COSMO4SUB will be investigated in a further ongoing work. It is important to further emphasize that the proposed framework is tailored for estimating the design hydrograph or the design simulation, so it aims to appropriately reproduce extreme events for small and ungauged basin.

In order to avoid any bias due to the inherent approximation of a generic rainfall simulator, in the present work we use the UCCLE rainfall time series that is a perfect input for testing the entire framework (Demarée, 2003; Tu Pham et al, 2018).

Since it is not necessary to hypothesize a design hyetograph with all related parameters, as in the common event-based approaches, the second step of a continuous framework is the excess rainfall estimation. In the previous version of COSMO4SUB, the standard NRCS-CN method was implemented. However, following the interesting debate present in literature (Eli and Lamont, 2010) we are aware that this method is not appropriate to be applied at sub-daily scale and in continuous framework. Such “abuse” (Garen and Moore, 2005) motivated us to deeper investigate on this problem identifying a solution in merging the NRCS-CN method with the Green-Ampt (GA) equation (Green and Ampt, 1911). As a result, the CN4GA model (Grimaldi et al., 2013a, 2013b) is proposed and here applied. In practice, the proposed approach applies the NRCS-CN method to quantify the excess rainfall depth, as recommended and expected, at event scale, and uses the GA equation to distribute in time the contributions to this depth. The GA parameters are estimated constraining the equation to give the total excess rainfall depth equal to that estimated by NRCS-CN, preserving the entire procedure as calibration-free. In Appendix A.1 some details of the procedure are briefly recalled and illustrated.

In previous studies, the practical effect of CN4GA approach was investigated at the event scale and the results obtained using observed rainfall-runoff events suggest that the NRCS-CN method tend to underestimate the peak discharge due to an inappropriate effect of initial abstraction on the hyetograph peaks. The present work is going to

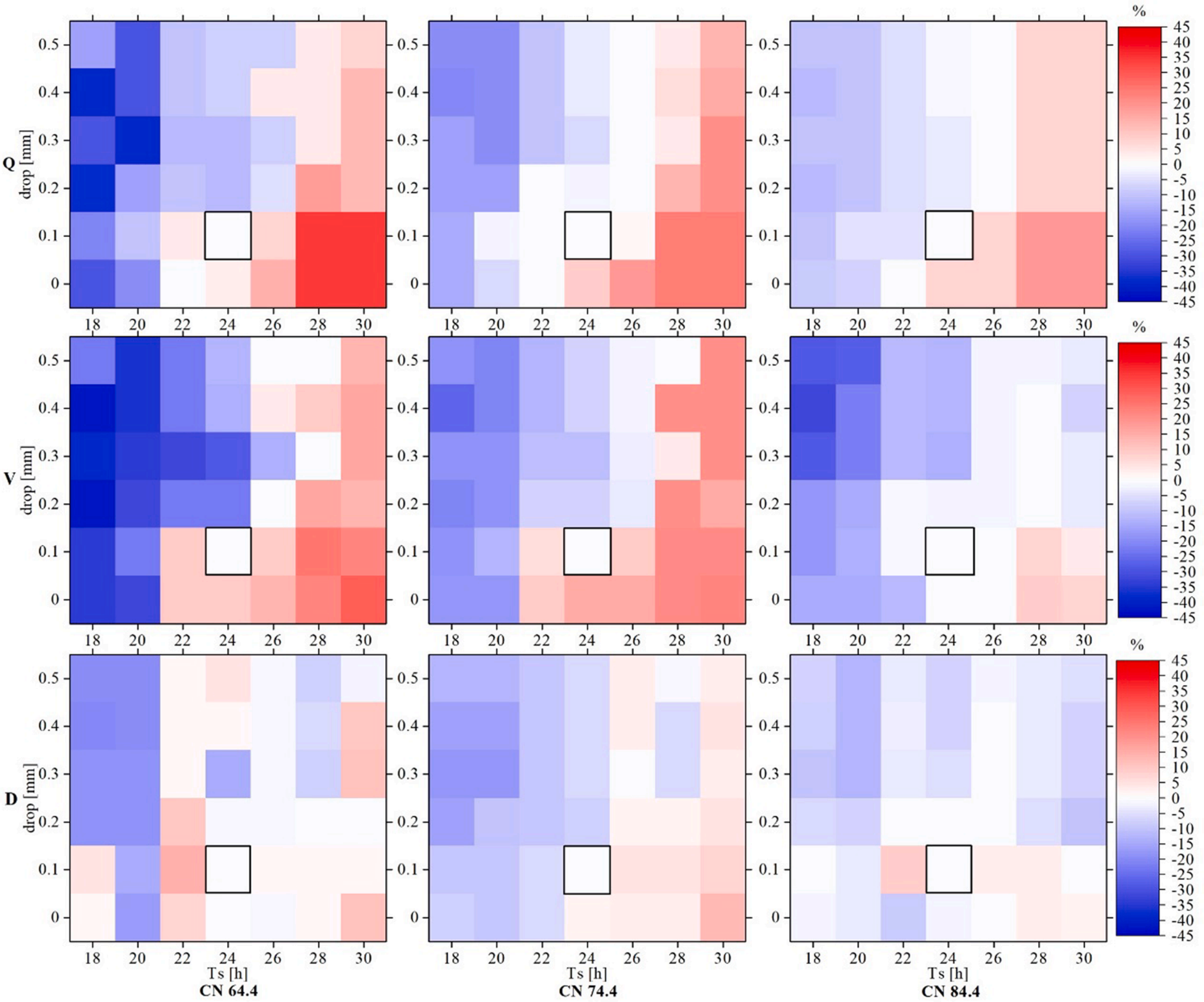

Fig. 4. *Ts* (x-axis) and *drop* (y-axis) parameter analysis. Rows indicate *Q, V, D* values related to the 80% quantile of annual maximum event selection with *Q* as driving variable. Columns refer to three different CN values. Black contoured cells are the reference "basic" model configuration. Each cell represents a model configuration with *Ts* and *drop* input values and the color quantify the percentage difference to the reference configuration. The white color of the reference cell corresponds to 0%.

further verify the effect of CN4GA when applied in a continuous framework using as input an observed long rainfall time series. We are aware that the NRCS-CN approach is not the best method available for a continuous model, indeed it does not include intra-event soil moisture condition module. However, since it allows to minimize the input information, it is appropriate for COSMO4SUB model being tailored to small and ungauged basin. One of the various drawbacks is that it still makes necessary, although in contradiction to the continuous set up, a sort of rainfall event identification through an additional parameter that we named separation time (*Ts*). This parameter represents the dry period (or almost dry) that should be waited so that the initial abstraction became again effective. In previous work the sensitivity of this parameter was analyzed using long synthetic rainfall time series: its effect on the design hydrograph was minimal and apparently 24 h, as suggested by NRCS-CN implementation (Fennessey, 2001), is a reasonable value to be used. In the present manuscript the sensitivity is further verified introducing also a different definition of *Ts* that is the period, not dry, but in which a minimal amount of rainfall (named "*drop*" parameter) is observed. Fig. 2 describes the meaning of these parameters (*Ts* and *drop*), their influence on the hydrograph and the interaction with T_c. The *Ts* effect is limited to the excess rainfall estimation: when the time distance between two storms is less than the separation time, the CN4GA method is applied on the sequence of the two storms considered as a unique event (Case A in Fig. 2). On the contrary (Case B) they are analyzed as two independent rainfall events. This characterization affects the total gross precipitation amount and the Antecedent Moisture Condition (AMC) 5-days values. In both cases the resulting flood hydrographs. are influenced by the convolution of the unit hydrograph and so by the concentration time.

The third step of the procedure is the excess rainfall-runoff transformation. The WFIUH model is applied for convoluting excess rainfall into runoff time series. Concerning this step, no specific modifications are introduced comparing to the original COSMO4SUB version. In our opinion the WFIUH approach, appropriately modified for ungauged conditions (Grimaldi et al., 2012c), is the most efficient method available since it allows to optimize the available digital topography information enforcing hydrogeomorphic processes that represent governing factors of floodplain generation dynamics (Annis et al., 2019; Nardi et al., 2018, 2019). For sake of brevity, here, WFIUH computational details are not reported and the reader can refer to Grimaldi et al. (2012c). The breakthrough innovative IUH definition as travel time distribution of watershed DEM cells (Rodriguez-Iturbe and Rinaldo, 1997) opened the way to provide a calibration free IUH. Flow path, hillslope-channel discrimination, velocity estimation on hillslopes are easy step useful to quantify the flow time or travel time distribution. Since the expected final user of COSMO4SUB is the practitioner that in

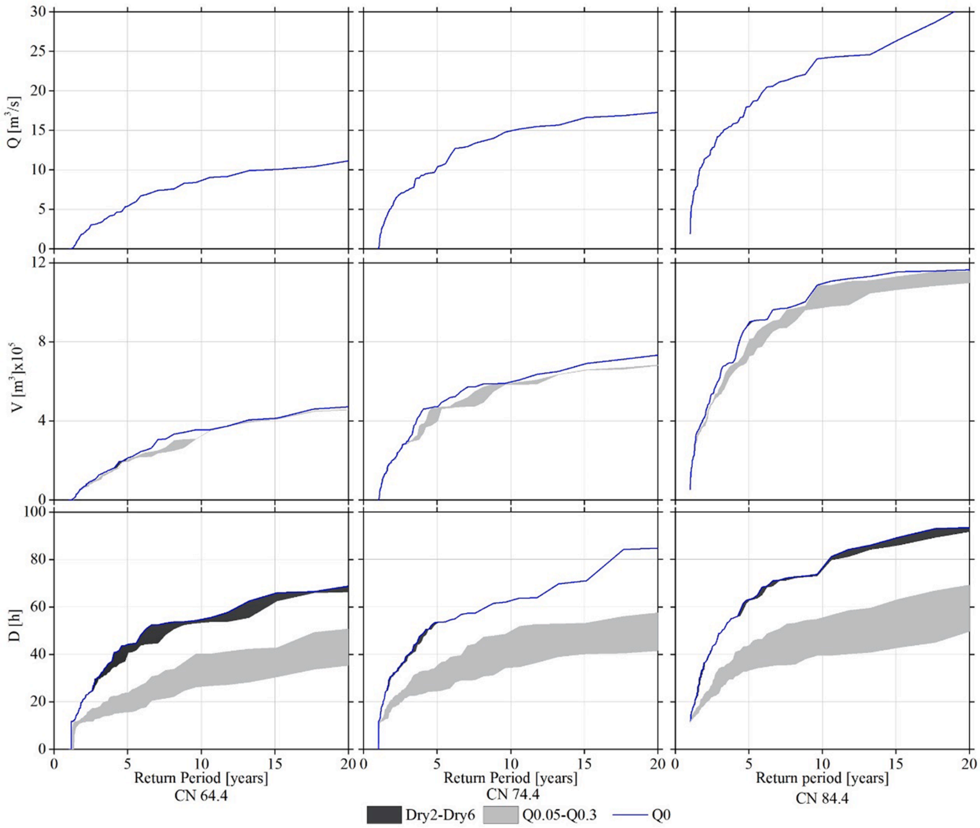

Fig. 5. Hydrograph selection strategies analysis (Test 3). Comparison of *Q-V-D* values related to different return periods varying the 12 scenarios listed in Table 2. Rows refer to the hydrograph attributes and columns to the CN values. The blue line represents the reference scenario (see n.7 in Table 2). Black and gray areas are the envelops of *Dry* and *Q-threshold* scenarios respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

similar context would have applied the rational formula, we prefer to constrain the channel velocity to the concentration time (or to the lag time). This procedural step includes two parameters to be assigned by the user. While the hillslope velocities are empirically quantified using distributed slope and land cover information, the contributing area threshold, useful to discriminate channel and hillslope cells, and concentration time should be preliminarily quantified. The first one has a minor impact on the final results while the second one, much more impacting, is typically estimated using empirical formulas (Petroselli and Grimaldi, 2018).

Once the entire runoff time series is estimated, in the last step the design simulation strategy is implemented. There are several options available that could be applied depending on the hydrological application. The practitioner could: directly apply the simulated runoff time series (Grimaldi et al., 2013c; Sikorska et al., 2018); select the design peak discharge applying a common flood frequency analysis on the extreme values (De Paola et al., 2018); estimate the design hydrograph (Serinaldi and Grimaldi; 2011, Brunner et al. 2017); or, apply a Montecarlo approach using the entire sample of simulated hydrographs (Annis et al., 2020). For the two latter options, it is necessary to appropriately isolate flood events preventing overestimation and underestimation of hydrograph volume and durations. In Section 4 a specific analysis is provided to support the assessment of the different possible approaches.

4. COSMO4SUB testing

This section presents a sensitivity analysis of COSMO4SUB modules and parameters. Specifically, the following five tests are described: Test 1) comparing effects of CN4GA as respect to the NRCS-CN approaches; Test 2) the sensitivity of design parameters to varying *Ts* and *drop* parameters; Test 3) comparing methods to extract flood hydrograph events from the simulated continuous flow time-series; Test 4) the influence of the sample selection criteria for flood frequency analysis; Test 5) the computational time reduction. The five tests are conducted varying methods and parameter values as respect to reference COSMO4SUB model configuration. The reference COSMO4SUB model for the case study is defined assuming the parameter values listed in Table 2 and selecting extreme events using the annual maximum method with the peak discharge *Q* as driving variable.

4.1. Test 1. CN4GA vs NRCS-CN

As mentioned in Section 3 and in Appendix A.1, the CN4GA method was previously tested in event-based hydrologic modelling analyses. This test aims to verify if the NRCS-CN modelling behavior (i.e. flood peak underestimation in particular) is confirmed in a continuous modelling approach using a long observed time series as input. The CN4GA and NRCS-CN excess rainfall estimation methods are both applied using the reference model parameter set-up. The resulting hydrograph characteristics (Peak, Volume, Duration) are compared and discussed. Considering the impact of varying CN parameter, the simulations are replicated using CN = 74,4 and 84,4.

4.1.1. Test 2. Ts and drop parameters

In this test the influence of *Ts* and *drop* parameters is assessed in terms of flood event selection within the continuous time series. As previously mentioned and illustrated in Fig. 2, two events are considered to be disconnected if, within a certain duration (*Ts*), a certain negligible rainfall amount (*drop*) is detected. The *drop* parameter is introduced for filtering out very minor rainfall depths that could impact the flood event filtering process.

Starting from the reference model configuration, *Ts* and *drop* are varied respectively from 18 to 30 h with incremental steps of 2 h and from 0 to 0.5 mm with incremental steps of 0.05 mm. The aim of the analysis is to verify the sensitivity of the hydrograph characteristics

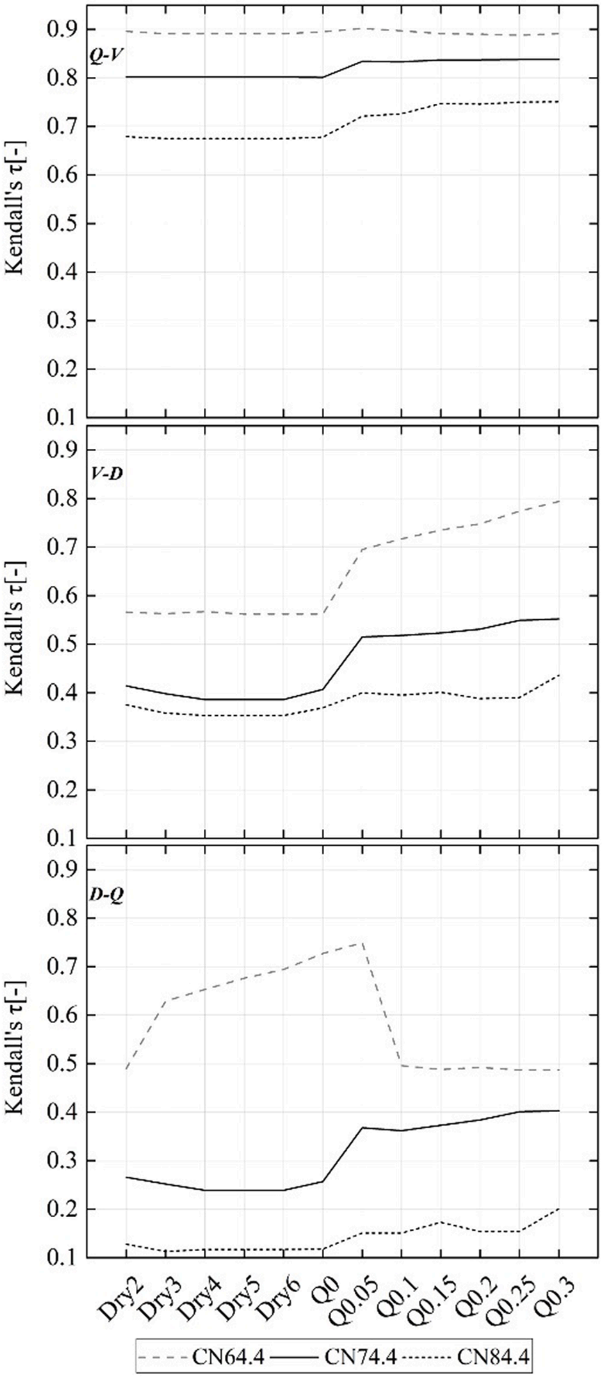

Fig. 6. Hydrograph selection strategies analysis (Test 3). Comparison of Kendall's ι values estimated on *Q-V* (first plot), *V-D* (second plot), *D-Q* (third plot) pairs varying the scenarios (in x-axis). Dashed gray lines refer to CN = 64.4; black line to CN = 74.4, and dashed black line to CN = 84.4.

(discharge, volume and duration) to varying *Ts* and *drop* parameters.

4.1.2. Test 3. Hydrograph selection

Continuous model output is a long runoff time series at high time resolution. The user is, thus, requested to extract hydrographs from the simulated series. This is common straightforward practice in case of runoff time series in absence of sub-surface and base flows. The two main approaches generally adopted are: (1) selecting the hydrograph starting from the first $Q > 0$ value and ending when the $Q = 0$; (2) introducing a threshold Qs value for filtering the time series ($Q > Qs$) and selecting hydrographs as in (1). It is noted that the two different approaches determine significant differences in the obtained hydrograph volume and duration. The approach selection shall be, thus, performed in relation to the design application. For instance, in case of high time resolution (like in the present case study of 10 min), adopting approach (1) two runoff events could be separated just because there are 10 min of null discharge. In order to verify the practical differences in the hydrograph selection approaches twelve configurations, as listed in Table 3, are tested applying the reference configuration model.

4.1.3. Test 4. Extreme hydrograph selection

A further issue, often neglected, relating to the synthetic design hydrograph characterization, is the extreme event selection (Brunner et al., 2017). While the design peak discharge estimation is quite straightforward, the design extreme hydrograph is not a trivial step. In fact, in this case, three important hydrograph attributes are considered. The common approach is selecting the maximum annual values referring to the peak discharge as “driving variable” and, once the event is identified, the triplets (Peak-*Q*, Volume-*V*, Duration-*D*) are estimated. This is a well known problem in extreme analysis since this approach not necessary select extreme values for *V* and *D* and this should be taken into account in the statistical analysis. Analogously to test 3, the optimal methodology strictly depends on the design application. For instance, the driving variable could be another attribute and not necessarily *Q*.

In order to assess the effect of this procedural step on the corresponding extreme event selection, three scenarios are compared:

- The common annual maximum value (AMV) using *Q* as driving variable;
- The peak over threshold using *Q* as driving variable, with a threshold level giving nearly the same sample size of AMV;
- A bivariate extreme value selection, choosing all the events with a joint non-exceedance probability value of *Q-V* higher than a threshold, fixed to give a sample size similar to those of the other scenarios. The joint non-exceedance probability is empirically estimated.

This third scenario includes only the *Q-V* values because *D* is not usually relevant in design estimation and because it is an unstable parameter (i.e. *D* is too variable to be considered as driving variable in the event selection approach). The comparison is provided applying the basic configuration with three CN values: 64.4, 74.4, 84.4.

4.1.4. Test 5. Computational time reduction

In the present paper, the 105-years long 10-minutes resolution rainfall time series determine a computational time of few minutes for running the COSMO4SUB model on a common personal computer (PC). Considering that the final model configuration will be provided as input a synthetic rainfall time series of 500 years or 1000 years at 10 min of resolution, the computational burden could be an issue for the effective transitioning to continuous modelling in practical applications. This could be amplified considering that the computational time should also include the calibration and simulation of the rainfall synthetic time series module and, in practical application, several framework running to identify appropriate model parameter values. In order to reduce the computational time a possible solution is to reduce the number of processed rainfall events, considering that the excess rainfall calculation is one of the major computationally intense steps. Assuming that, while aiming to estimate the design hydrographs, the interest is linked to events with higher magnitude, filtering out very minor rainfall events should have negligible impact on the design variables. In practical terms, the solution for optimizing the computation process is to remove all events characterized by a total excess rainfall amount that is lower than a predefined threshold. Consequently, the computational time reduction and the effect in the flood frequency analysis are verified.

Starting from the reference model configuration, for a specific CN

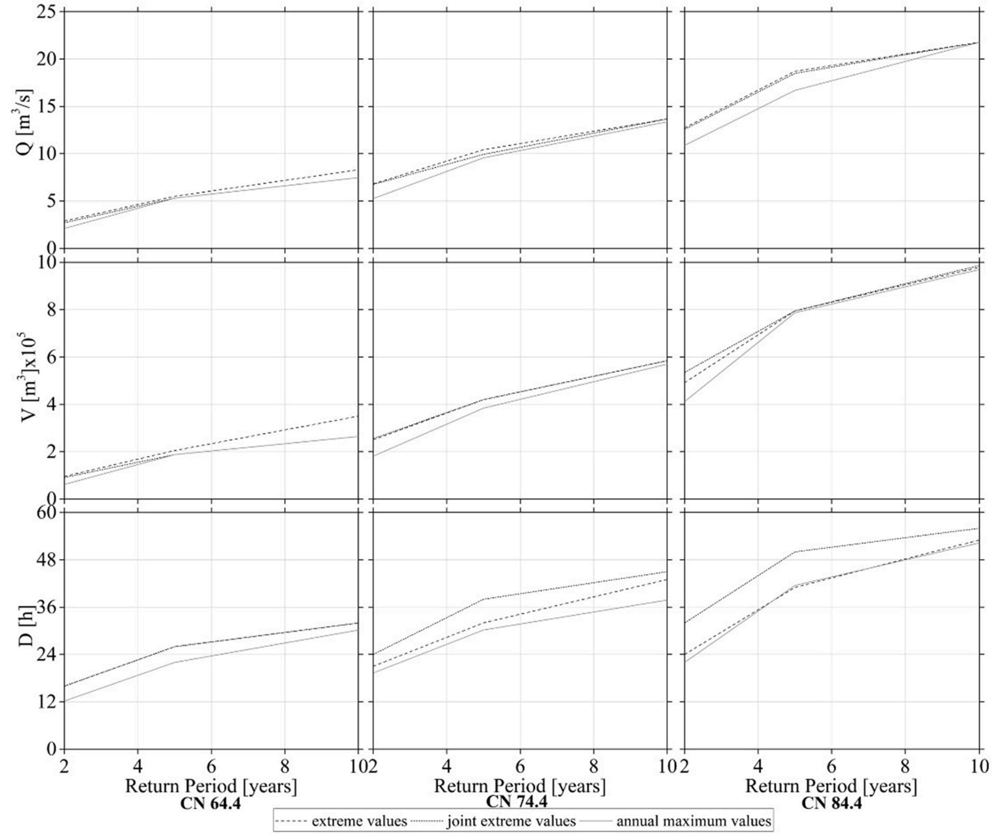

Fig. 7. Extreme event selection (Test 4). Rows: *Q-V-D* related to different return periods estimated with different CN values (columns). Dashed black line refers to extreme value selection; small dashed black lines to joint extreme values and gray line to the common annual maxima values.

value, 9 excess rainfall thresholds are tested considering a range starting from 0 to 2 mm with incremental step 0.25 mm. Since results could be strongly dependent on the CN (for higher CN values a corresponding higher number of rainfall events are available), the test is implemented for 7 CN values, from 55 to 85 with incremental step of 5.

5. Test results

Test 1 results are presented in the matrix plot of Fig. 3. The maximum annual triplets of *Q, V* and *D* values, selected using *Q* as driving variable, are shown to compare the varying results corresponding to the application of the NRCS-CN and CN4GA methods. The three columns refer respectively to three different CN values (64.4, 74.4, 84.4), while the rows correspond to the hydrograph attributes (*Q, V, D*). In each plot the two excess rainfall estimation methods are compared showing empirical return periods. In general, for the conducted tests, the comparison return period values are low and limited to 20 years. In fact, the length of the rainfall time series (105 years) does not allows to focus on more representative flood events.

Results of simulated peak discharge values confirm the attitude of the NRCS-CN method in underestimating *Q*. Indeed, the differences among the two curves are visible on the entire return period range, reach up –22.8% (for $Tr = 20$ years and CN = 84.4), and increasing for higher CN value. The volume variable overlapping is expected, considering the adopted CN4GA approach methodology (see Appendix A.1), that distributes in time the NRCS-CN excess rainfall cumulated depth (for matching volumes). The varying duration values suggest that, applying the CN4GA, we obtain hydrographs with shorter duration. This is also expected, in line with previous findings, align with the aim of providing excess rainfall event more intermittent and coherent to the natural rainfall behavior. The difference between the durations is homogenous for the entire range of return period and for the varying CN values, reaching up a −36.2% maximum variation (CN = 74.4 and $Tr = 10$ years).

Test 2 results are presented in Fig. 4 illustrating the outcomes of the sensitivity analysis with varying *Ts* and *drop* parameters. Matrix plots are used with columns referring to different CN values and rows showing the hydrograph attributes (*Q, V, D*). Each sub-plot presents a raster where hydrograph attributes are the cell value corresponding to model configuration associated to *Ts* and *drop* X- and Y-axes. The cell values are color-coded as a function of the percentage of difference to the reference model configuration (also depicted as no-variation white cell). This latter is highlighted with black contour. The three attributes (*Q, V, D*) corresponds to the 80% quantile of the maximum annual values using *Q* as driving variable. While in the proximity of the reference model configuration the differences are limited (±5–10%), for the present case, an higher variability compared to the previous studies (Grimaldi et al 2012a) is quite visible. In order to clarify the remarkable differences obtained, it is useful to recall the effect of *Ts* parameter. Increasing the *Ts* it is expected to have longer rainfall events, a larger amount of gross and excess rainfall and, consequently, higher peak discharge, volume, and hydrograph duration. A secondary and opposite effect could also concur to determine such differences, considering that longer rainfall event may group more than a single event, and a decreasing AMC class can arise causing reduction of peak discharge, volume and duration. These two opposite effects strive to be balanced when a large number of events are available. In previous investigations (Grimaldi et al. 2012a), 500 years of synthetic rainfall series were analyzed. This can motivate the test outcomes that, with only 105 years of series length, the *Ts* produces more variable results. This suggests that long time series are necessary and future research will be useful to verify such behavior with increasing time series length, probably towards 1000 years. Furthermore, a minor concurring cause, of such a significant variability, is related to the different excess rainfall estimation methods. The CN4GA method, as

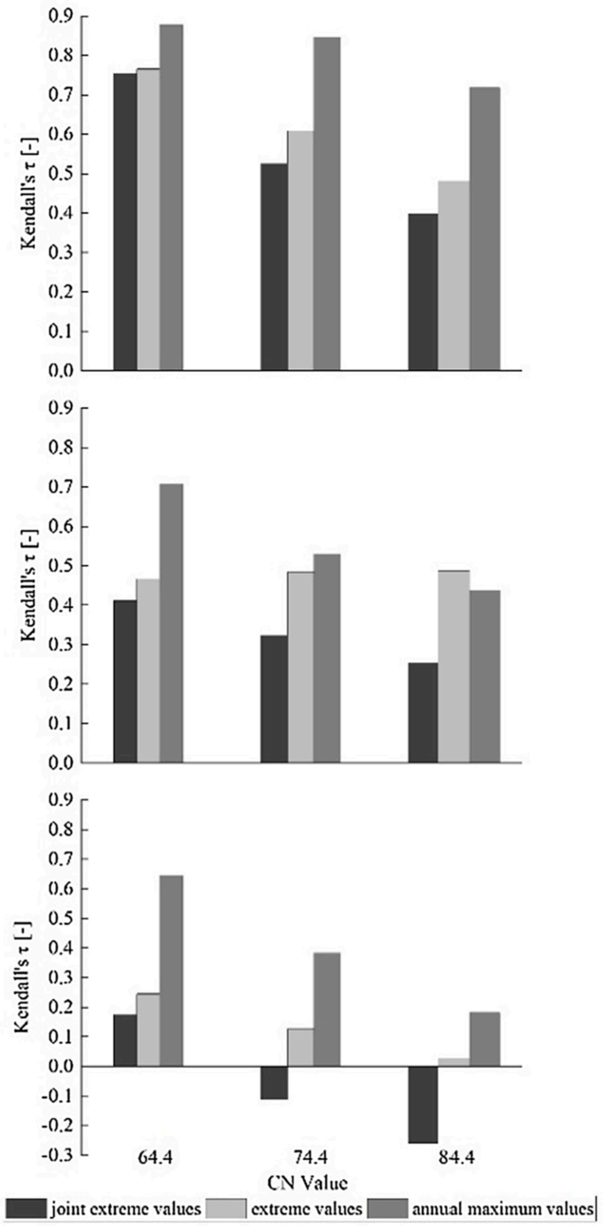

Fig. 8. Extreme event selection (Test 4). Kendall's ι estimated on *P-V* (first plot from above), *V-D* (second plot), *D-Q* (third plot) pairs for different CNs. Different gray scales are related to the event selections strategies.

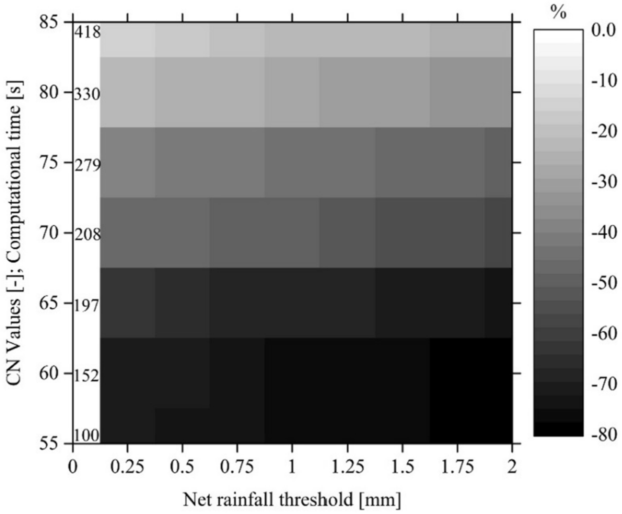

Fig. 9. Computational time reduction (Test 5). In x-axis the excess rainfall threshold, in y-axis CN values. The first column from the left reports reference basic model configuration computation times without any excess rainfall threshold application. Each cell is related to a combination of CN and excess rainfall threshold and its gray scale color refers to the percentage difference respect to the reference basic model configuration.

shown in Fig. 3, is characterized by more intermitted storms with higher variance that can amplify the *Ts* variability effects especially when considering relatively short input rainfall time series.

Test 3 results, reporting the impact of the hydrograph selection strategies, are illustrated in Figs. 5 and 6. Fig. 5 compares the *Q, V* and *D* values, associated to empirical return periods, obtained with the varying scenarios listed in Table 2. The comparison is repeated for three CN values. The blue line represents the reference model configuration (Scenario n. 7 – Q0). The black area includes the envelopes of results corresponding to the five *Dry* scenarios (n. 8- n.12), while the gray area reports the six *Q-threshold* scenarios (n. 1- n. 6). The plots missing to include the black and gray areas show the absence of variability with scenarios overlapping to the reference model configuration. This is evident by looking at the first row of the *Q* plots where, by definition, any variability could occur. Concerning volumes, shown in the second row of the matrix plot, the *Dry* scenarios exhibit no significative divergence from the reference values while, for the *Q-threshold* scenarios, a limited variation is visible, higher for the CN = 84.4 that reaches −11,2% for the scenario *Q03*.

As expected, duration values are significantly affected by the selection strategies. However, it is confirmed the minor effect of *Dry* compared to the *Q-threshold* scenarios. Specifically, duration values can show variations till to −51,2% for the scenario *Q03*.

Fig. 6 provides a comparison among the different scenarios from a different perspective. Indeed, the Kendall's τ dependence measure estimated on pairs (*Q-V; V-D; D-Q*) are shown. Results suggest that dependence structure of *Q-V* is not affected by the hydrograph selection strategies, while the differences become more relevant for *V-D* and *D-Q*. For this latter the variability is more significant for low CN values.

Results does not support to extrapolate general conclusions since they are related to a specific case study. However, it is evident that the duration variable appears to be particularly influenced by the different hydrograph selection strategies and the volumes are also particularly impacted by varying CN values. Future analyses on different case studies and using longer synthetic time series are needed to investigate and generalize such modelling behavior.

Results of test 4, on the extreme hydrograph selection analysis, are depicted in Figs. 7 and 8. The first one compares *Q-V-D* for several return periods using different extreme event selection methods (extreme values - EV; joint extreme values - JEV, and annual maximum values - AMV). Concerning *Q* and *V*, results are similar with a tendency to be equal considering EV and JEV. While, as expected, *D* is more affected by the sampling strategies reaching more significant differences as in the case CN = 84.4 and Tr 4 years, where JEV and EV-AMV differ of + 25%. Fig. 8 provides an overview of the same comparison test using the Kendall's τ. Here, results appear significantly different suggesting the attitude of AMV to provide more correlated pairs. Differences increase with the increase of CN values and more prominently for the *D* variable, impacting a possible multivariate frequency analysis. The discrepancies related to varying CN values are justified by the larger number of events produced with higher CN values. So, this is resulting in a reduction of the correlation related to the application of the JEV strategy since for each peak discharge value several possible volumes are possible and available. The lower τ for JEV, evident in general, is due to the inclusion of flood events maximizing their volume, and consequently their duration. This is determining a variety of events that are necessarily less correlated.

Finally, the last test results related to the COSMO4SUB computational times, varying CN values and reduction strategies (Test 5), are available in Fig. 9. The first column values represent the computational times corresponding to model applications without any excess rainfall restrictions while varying CN values (y-axis). Computation times vary from a minimum of 100 s for the CN = 55 to the maximum of 418 s for CN = 85. Indeed for higher CN values larger number of rainfall events need to be processed. Applying a higher excess rainfall threshold (x-axis values), that is removing all the storms with cumulative excess rainfall depth less than a fixed value, a reduction of the computational time is assesses. This is shown in Fig. 9 where the gray scale cells refer to the percentage of reduction as respect to the reference model configuration. Interesting to note that with only a 0.25 mm threshold a significant computational time reduction is obtained (-50% for CN = 70). and that all configurations, shown in Fig. 9, do not significantly alter (not shown here for the sake of brevity) the extreme event properties.

6. Conclusions

Continuous rainfall-runoff modelling frameworks are reaching maturity for hydrologic modelling on small and ungauged basins with limited (or lacking) flow records. Remote sensing, hydrologic monitoring and modelling advancements, driving such modelling evolution, allow continuous models to provide more accurate and more versatile outputs that may be tailored for a variety of hydrological applications. In the present contribution improvements of a continuous simulation model, named COSMO4SUB, are described and tested. An advanced excess rainfall estimation module (CN4GA) and sensitivity analyses are provided using as input a very long rainfall time series (105 years) observed at 10 min of resolution. This represents an excellent case study considering this rainfall time series overcomes the issue of synthetic rainfall time series. The case study results support some conclusions that in future researches can be verified using longer synthetic rainfall time series. The CN4GA module performed well in the continuous framework confirming its attitude shown in previous contributions where it was applied at event-based analysis. The separation time parameter, necessary to separate the rainfall events for applying the CN4GA method, confirmed an encouraging limited variability although higher compared to previous analysis, suggesting for future application of the framework to use a longer input time series (possibly 1000 years). Hydrograph and extreme event selection strategies, typically neglected in the hydrological studies, needs to be seriously considered and standardized since its impact could affect final design output. The computation time is coherent to the common modelling tools applied in hydrological studies and can be reduced without altering the final output.

Although further analyses are necessary to reach more general conclusions and to identify the optimal rainfall simulation model useful for such continuous modelling, it is already possible to affirm that it is worth to apply a continuous model in small and ungauged basins by the professional community since it offers some useful ameliorations in the design hydrograph estimation and consequently in the design simulation.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A.1

NRCS-CN procedure

For each gross rainfall event, the time distribution of the cumulative excess rainfall $P_{NRCS}(t)$ (mm) is estimated according to the following formula (NRCS, 2008):

$$P_{NRCS}(\mathrm{t}) = \begin{cases} \dfrac{(P(t)-Ia)^2}{P(t)+S-Ia}\mathrm{for}P(t) \geq Ia \\ 0\mathrm{for}P(t) < Ia \end{cases} \tag{A.1}$$

where $P(t)$ (mm) is the time distribution of cumulative gross rainfall value, S (mm) is the maximum potential basin retention, and Ia (mm) is the initial abstraction due to the interception, infiltration and surface storage. S and Ia are a function of the Curve Number CN, as in the following:

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{A.2}$$

$$Ia = 0.2S$$

Assuming the cumulative gross rainfall time distribution is known, the excess rainfall $p_{NRCS}(t)$ (mm/step) can be obtained by differenciating the $P_{NRCS}(t)$ cumulative values.

CN4GA procedure

The CN4GA procedure merges the NRCS-CN method and the following Green-Ampt (1911) equation:

$$\mathrm{i}(t) = \begin{cases} p(t)\mathrm{for}t < t_{\mathrm{pond}} \\ K_{\mathrm{S}}\left(1 + \dfrac{N_{\mathrm{s}}}{I(t)}\right)\mathrm{for}t > t_{\mathrm{pond}} \end{cases} \tag{A.3}$$

where i (mm/step) is the infiltration rate, $p(t)$ (mm/step) is the gross rainfall intensity, t_{pond} (h) is the ponding time, I (mm) is the cumulative infiltration, K_s is the saturated hydraulic conductivity (mm/h), and N_s is the soil moisture-tension parameter (mm).

In the mixed procedure we assume that t_{pond} is reached when $P(t)$ equals to Ia, this means that both NRCS-CN and CN4GA have the same ponding time. Moreover, K_s is calibrated so that the excess rainfall cumulative value obtained by the CN4GA method equals to the corresponding one computed by the NRCS-CN method.

From a practical point of view, starting from the previously estimated P_{NRCS} value, the Green-Ampt equation is firstly applied using literature values for K_s and N_s parameters. Consequently, the cumulative value for excess rainfall, P_{CN4GA}, is calculated and compared to the P_{NRCS} value, and the following three cases can occur:

1) $P_{CN4GA} = P_{NRCS}$ (tolerance is set as 0.1 mm), in this case the CN4GA procedure converges.
2) $P_{CN4GA} < P_{NRCS}$, in this case Green-Ampt equation is solved again using a lower value for K_s, which means a lower infiltration and a higher excess rainfall. K_s value is iteratively reduced by δ amount until P_{CN4GA} and P_{NRCS} converge and δ is smoothly reduced to give finer convergence to the iterative procedure.

3) $P_{CN4GA} > P_{NRCS}$, in this case Green-Ampt equation is solved again using a higher value for K_s, which means a higher infiltration and a lower excess rainfall. K_s value is iteratively increased by δ until P_{CN4GA} and P_{NRCS} become equal. Again, δ is smoothly reduced to give finer convergence to the iterative procedure.

At the convergence of the iterative procedure, a calibrated value for K_s is quantified and the excess rainfall time series p_{CN4GA} is estimated through the A.3 equation. Further details on this procedure are available in Grimaldi et al. (2013a) and Grimaldi et al. (2013b), also concerning the negligible sensitivity of A.3 equation parameters that determine CN4GA as a calibration free procedure.

Both procedures are based on the Antecedent Moisture Condition (AMC) evaluation that constrains CN values to some climatic variables observed five days antecedent to the rainfall event. In particular the AMC selection is performed according to the official NRCS (2008) formulation, evaluating the cumulative rainfall in the 5 days before the generic rainfall event (P5d) and considering the vegetation growing season (assumed from May to November) or dormant season (assumed from December to April). AMC I (dry condition of soil) is assigned when P5d is lower than 12.7 mm (dormant season) or lower than 35.6 mm (growing season). AMC II (normal or average condition) is assigned for P5d ranging between 12.7 mm and 27.9 mm (dormant season) or ranging between 35.6 mm and 53.3 mm (growing season). AMC III (wet condition for soil) is assigned when P5d higher than 27.9 mm (dormant season) or higher than 53.3 mm (growing season). When AMC is equal to II, the original CN value estimated based on look tables on land cover and soil type is selected (CN-II), otherwise CN value is modified as in the following:

$$CN(I) = \frac{4.2*CN(II)}{10 - 0.058*CN(II)}, forAMCI$$

$$CN(III) = \frac{23*CN(II)}{10 + 0.13*CN(II)}, forAMCIII$$

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