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Design hydrograph estimation in small and fully ungauged basins: a preliminary assessment of the EBA4SUB framework

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Abstract

Design hydrograph estimation in small and ungauged basins is still a critical issue in hydrological studies. Although a great effort has been devoted to improving the knowledge on this topic in the last 10 years, some unresolved problems still limit the practitioners. Indeed, in small and ungauged watersheds located in areas where regionalisation analyses are not available, hydrologists still typically apply the rational formula. In a recent contribution, we proposed an event-based framework illustrating its potential benefits over the widely used rational formula and underlining its tendency to be less sensitive and less subjective. In the present contribution, we present a preliminary assessment of the proposed framework, analysing its application to five watersheds for which enough observed data are available to provide an evaluation of the model's performance. Although the results confirm that the design hydrograph estimation in small and ungauged basins is affected by relevant errors and uncertainty, they also show that the proposed framework is promising for practical hydrology.

Introduction

The last decade has been marked by the successful initiative of International Association of Hydrological Sciences – Prediction in Ungauged Basins (IAHS-PUB; Sivapalan *et al*., 2003; Bloeschl *et al*., 2013; Hrachowitz *et al*., 2013), which collected wide interest and numerous contributions from the scientific and professional community on the crucial problem of predicting hydrological processes in watersheds lacking in observations. A significant effort was devoted to regionalisation procedures to overcome the absence of data; however, for small watersheds, located in heterogeneous areas where it is not possible to extend information from similar basins, empirical approaches are still the only methods available for practitioners (Efstratiadis *et al*., 2013). Indeed, in the specific case of design peak discharge estimation in small and ungauged basins, the rational formula (Mulvaney, 1851; Kuichling, 1889; Chow *et al*., 1988; Dhakal *et al*., 2013a,b) is still widely applied and is recommended by river basin authorities (i.e. for Italy: PAI, 2006).

Our recent contribution (Grimaldi and Petroselli, 2015) underlined the need to propose an alternative empirical procedure to the rational formula, with which the same basic input information could be used to provide less sensitive and less subjective results. The proposed framework, 'event-based approach for small and ungauged basins', named EBA4SUB, is designed to provide not only the peak discharge related to a return period but also the design hydrograph shape. The structure of the framework is organised using common event-based modules including the hyetograph design, the rainfall excess estimation, and the rainfall-runoff transformation. In EBA4SUB, modified versions of these well-known modules are appropriately adapted to be correctly and precisely applied in fully ungauged area, using the same input information needed for the rational formula [intensity–duration–frequency (IDF) curves and soil use]. The only required additional input is a watershed digital elevation model, which is currently freely available around the globe.

As stated in Grimaldi and Petroselli (2015), the added value of EBA4SUB is not to provide a better estimation of the design peak discharge, but to offer a less sensitive and less subjective procedure. We believe that it is difficult or impossible for an empirical framework that uses such poor and limited input information to provide good results in comparison with observed values. Indeed, we are convinced that an effective empirical model should only provide realistic discharges with a low degree of sensitivity and subjectivity.

Here, with the term 'subjectivity' we refer to the arbitrary degree of the practitioner and consequently to his/her freedom in assigning model parameter values without associating it a clear technical motivation. For instance, the choice of run-off coefficient value within a range can be done with a vague motivation and, in practice, it gives the opportunity to the practitioner to decide the model output. In Grimaldi and Petroselli (2015) it was shown that for the rational formula, for a specific soil use class, the run-off coefficient range leads to a range of peak discharge values that differ more than 100%. Similarly, here, with the term 'sensitivity', we refer to the degree of variability of the output compared to, or induced by, the variability of the input. When the sensitivity is particularly high, it increases the subjectivity of the analyst. A clear example is given by the concentration time, indeed its estimation is affected by dramatic uncertainty (Grimaldi *et al*., 2012a) having a crucial consequence in peak discharge estimation using rational formula. Indeed, again, the practitioner can adopt the concentration time formula that provides the desired peak discharge value. In conclusion, in our opinion, it would be useful for a model to be able to be applied to the same watershed and with the same input data, twice, by two different users, in two different instances, giving the same or at least similar results. In Grimaldi and Petroselli (2015), we showed that the rational formula suffers from high sensitivity to the concentration time and from high subjectivity due to the run-off coefficient, while the proposed procedure is designed to reduce this tendency.

Starting from these premises and from results described in Grimaldi and Petroselli (2015), where we focused specifically on the comparison between rational formula and the proposed framework, here in this work we provide a preliminary assessment of EBA4SUB.

The aims of this paper are: (1) to preliminary validate the proposed model analysing five small watersheds for which several years of maximum annual peak discharge observations are available; (2) to understand the behaviour of the model through the case studies application; (3) most importantly, to investigate on the role of secondary parameters included in the framework, such as design hyetograph peak position and time resolution. Indeed, they can be arbitrarily chosen by the practitioner and consequently it is important to verify how they affect the model results.

The manuscript is organised as follows. In the next section, the EBA4SUB framework is summarised and discussed, while in section 'Description of case studies', the five watersheds are depicted. Section 'EBA4SUB framework analysis' investigates on the peak position and time resolution, showing that these factors do not significantly influence the peak estimation, and finally, an evaluation of EBA4SUB is presented, comparing observed and simulated data.

EBA4SUB framework

As explained, EBA4SUB allows the estimation of the peak discharge and the related hydrograph assigned to a return period and consists of three steps briefly discussed in the following sections. The framework is designed with the aim to be as simple as possible, like the rational formula, with minimum input information. For this, we referred to well-known procedures widely applied in practice. The novelty included in EBA4SUB are mainly related to the net rainfall module that is based on the recently proposed mixed Curve Number – Green Ampt procedure and to the rainfall-run-off module that is based on a parsimonious adaptation of the width function geomorphological unit hydrograph. Further details of each module are available in Grimaldi and Petroselli (2015).

Design hyetograph

In the literature, several design hyetographs have been compared; for instance, in Alfieri *et al*. (2008), the Chicago formulation (Keifer and Chu, 1957) appeared to provide the best performance when compared to the variational, rational, and best linear unbiased estimation (BLUE) formulations, and it has therefore been selected for use in this framework. As highlighted by Alfieri *et al*. (2008), the Chicago hyetograph can present an excessive rainfall peak intensity: for instance, in the aforementioned manuscript, Chicago rainfall peak intensity was 3.5 times greater than that found using the BLUE approach, 4.2 times greater than with the variational approach and 7 times greater than with the rational approach. Moreover, these results emphasise that hyetographs presenting constant rainfall intensity tend to underestimate the peak flow, in particular for the rational approach when presenting duration equal to the concentration time, while overestimation can occur when adopting the Chicago hyetograph. Such circumstances could be useful in flood risk modeling because Chicago hyetograph could represent an upper threshold condition for peak discharge determination, allowing the modeler to investigate the most critical situation.

Starting from IDF curves, it is possible to distribute the cumulative critical rainfall depth over time according to the following Chicago equations:

$$
\begin{aligned}
i(t,T_r) &= a(T_r)\,n(T_r)\left(\frac{t_p - t}{r_c}\right)^{n-1} \quad \mathit{for} \quad t \le t_p \\
i(t,T_r) &= a(T_r)\,n(T_r)\left(\frac{t - t_p}{1 - r_c}\right)^{n-1} \quad \mathit{for} \quad t > t_p
\end{aligned} \tag{1}
$$

where i is the rainfall intensity, t is the time, T_r is the return period, a and n are the coefficients of the IDF with two parameters, t_p is the peak position, and r_c is the ratio between the peak position and the rainfall duration. To apply the previous formula, the user just needs to specify a given return period and a critical rainfall duration, which usually is chosen equal to the basin concentration time, T_c. It is noteworthy that in the present work the Chicago hyetograph has been discretised employing the alternating block method (Chow *et al.*, 1988).

To determine the average gross rainfall needed in the rainfall run-off modeling, the Thiessen method and aerial reduction factor (ARF) must be applied to the rain gauges present in the selected basins; ARF is determined using the Leclerc and Schaake (1972) equation:

$$ARF = \frac{AR}{PR} = 1 - e^{\left(-1.1 * t^{0.25}\right)} + e^{\left(-1.1 * t^{0.25} - 0.0259A\right)} \quad (2)$$

where *AR* represents the cumulative areal rainfall (mm), *PR* is the cumulative point rainfall (mm), *t* is the rainfall duration (h), and *A* is the basin area (km^2).

Excess rainfall

Excess rainfall is estimated from the gross hyetograph using the recently proposed CN4GA procedure (Grimaldi *et al.*, 2013a, b); CN4GA combines in two steps the Soil Conservation Service – Curve Number (SCS-CN) method [Natural Resources Conservation Service (NRCS), 2008], which is one of the most commonly employed approaches for estimating cumulative net run-off from cumulative gross rainfall, and the Green-Ampt equation (Green and Ampt, 1911; Mein and Larson, 1973), which is one of the most widely used infiltration equations.

In the first step, the SCS-CN method is applied to determine the total net run-off and the ponding time, using the following equations:

$$\begin{aligned} P_e &= \frac{(P - I_a)^2}{P - I_a + S} \quad && if \quad P > I_a = \lambda S \\ P_e &= 0 && if \quad P \le I_a \end{aligned} \quad (3)$$

where P_e is the total net rainfall; *P* is the total gross rainfall, i.e. the previously determined *AR*; I_a is the initial abstraction, i.e. the cumulative rainfall required for the initiation of run-off; λ is the initial abstraction ratio, assumed to be equal to 0.2 as in the method's original formulation; and *S* is the potential maximum water retention, a function of the unique method parameter, the curve number (CN). CN represents an index ranging from 0 (soil use and type conditions for which all gross rainfall is lost and no run-off is allowed) to 100 (no losses, all gross rainfall becomes run-off), which is well classified for different hydrologic soil groups and land cover conditions. Ponding time, according to the previous formula, occurs when $P(t) = I_a$. In this step, the user only needs to specify the CN value, because the method here employs the original formulation where $\lambda = 0.2$ (Woodward *et al.*, 2010), although recent literature has suggested that λ is not a constant from storm to storm or from watershed to watershed and that the assumption $\lambda = 0.2$ is unusually high. However, if the user adopts the original CN tables, he must refer to the 0.2 value (Woodward *et al.*, 2010).

In the second step of the CN4GA procedure, the total net run-off provided by the SCS-CN method is applied as input to the following Green-Ampt equation:

$$\begin{aligned} q_0 &= i && for \quad t < t_p \\ q_0(t) &= K_s\left(1 + \frac{\Delta\theta\Delta H}{I(t)}\right) \quad && for \quad t > t_p \end{aligned} \quad (4)$$

where q_0 is the infiltration rate, *i* is the rainfall rate, $\Delta\theta$ is the change in soil-water content between the initial value and the field saturated soil-water content, *I(t)* is the cumulative infiltration, K_s is the saturated hydraulic conductivity, t_p is the ponding time, and ΔH is the difference between the pressure head at the soil surface and the matric pressure head at the moving wetting front. Regarding the Green-Ampt parameters, t_p is defined as the time when *P(t)* is equal to the initial abstraction I_a of the SCS-CN method, while the saturated hydraulic conductivity is automatically calibrated so that the total cumulative net run-off provided by the SCS-CN method is equal to the corresponding one provided by the Green-Ampt equation. The other Green-Ampt equation parameters, as highlighted in Grimaldi *et al.* (2013b), are insensitive when a dominant peak intensity is present in the design storm, such as in the observed rainfall and in the Chicago hyetograph, and then the parameter values can be fixed a priori starting from an average soil type. In conclusion, CN4GA allows the total net rainfall amount, estimated with the SCS-CN method, to be distributed over time at a subdaily resolution according to a physically based infiltration equation.

Design hydrograph

The design hydrograph is estimated by employing an advanced digital elevation models (DEM) preprocessing analysis and applying a parsimonious geomorphological instantaneous unit hydrograph (IUH).

The DEM is analysed as follows: (1) pits and flats are removed through the physically based PEM4PIT method (Grimaldi *et al.*, 2004, 2007; Santini *et al.*, 2009); (2) flow routing is defined using an optimised single flow direction method (Nardi *et al.*, 2008); and (3) the river network is extracted using the drop analysis approach (Tarboton *et al.*, 1991). Usually, DEM at 30-m resolution are appropriate for hydrological lumped modeling; when and where higher resolution is available they should be preferred (Petroselli, 2012).

The selected IUH is based on the width function framework (WFIUH-1par: Grimaldi *et al.*, 2010, 2012b) according to:

$$WFIUH(t)=\frac{L_c(x)}{v_c(x)}+\frac{L_h(x)}{v_h(x)} \quad (5)$$

where L_h and L_c are the hill slope and channel flow path functions of the DEM cell x, respectively, and v_h and v_c are the hill slope and channel flow velocities, respectively. While L_h and L_c are provided by the DEM according to the adopted flow routing scheme, v_h and v_c represent parameters affecting the basin response, i.e. the shape of the WFIUH (peak and base time). Recent contributions (Grimaldi *et al.*, 2010, 2012b) have suggested estimating v_h for each cell according to terrain hydrogeomorphic properties such as slope and land cover, and calibrating the channel velocity so that the WFIUH base time or centroid is equal to the concentration time or the lag time. Assuming the second condition, the user just needs to specify the basin lag time (T_L), which is linked to T_c through the relation $T_L = 0.6\ T_c$ (Chow *et al.*, 1988; Di Lazzaro, 2009).

Once WFIUH is defined, the hydrograph $Q(t)$ can be obtained through the convolution integral according to:

$$Q(t)=A\int_0^t WFIUH(t-\tau)P_n(\tau)d\tau \quad (6)$$

where A is the watershed area, t is the time and $P_n(t)$ is the CN4GA net rainfall.

Description of case studies

Five case studies were selected, located in different countries and characterised by different climatic regimes.

Three German watersheds (Ilme, Sieber and Boehme) were selected pertaining to the Aller-Leine river basin, located in the southeastern part of Lower Saxony. The Aller-Leine river basin has a heterogeneous landscape; the mountains in the southern part of the catchment are broadly covered by forests, the aquifers in this area are fractured, with some karst regions, and the climate is characterised by high annual precipitation and by frost in the winter season. The flatland dominating the northern part of the catchment is characterised by sandy soils, porous quaternary aquifers and heath and moor vegetation. For a detailed description of the Aller-Leine river basin, please refer to Wallner *et al.* (2012, 2013). IDF curves for different return periods T_r are available, and maximum monthly peak discharges have been observed from 1951 to 2005 thanks to the KOSTRA-DWD Program (2000). DEM at 30-m resolution and land cover data were retrieved, respectively, from the ASTER GDEM (2009) and CORINE (Coordination of Information on Environment) Database (2000) websites.

One French watershed (Orgeval) was selected, belonging to the Seine basin and located approximately 70 km east of Paris. The annual rainfall is approximately 700 mm, the climate is semi-oceanic, the basin soil top layer comprises silt, and the sublayer is mainly clay. Most of the basin's area is artificially drained and dominated by agricultural land (82% of the surface); the remaining surface is covered by woods (17% of the surface) and urban zones or roads (1% of the surface). For a detailed description of the Orgeval river basin, please refer to Vilain *et al.* (2012). Observed hourly precipitation and discharge data from 1970 to 2012 allowed the construction of IDF curves for different return periods (T_r) and the determination of yearly discharge maxima. In particular, the IDF data were determined by extracting yearly maxima with durations equal to 1 h, 3 h, 6 h, 12 h and 24 h from the rainfall database, using these to estimate two-parameter IDF curves. Rainfall and discharge data and a DEM at 50-m resolution were provided by GIS ORACLE – CEMAGREF, while land cover data were retrieved from CORINE (Coordination of Information on Environment) Database (2000) web site.

One Italian watershed (Samoggia) was selected, pertaining to the Reno river basin and located in northern central Italy; the mountain areas here are mostly covered by broad-leaved woods, while the bottom valleys are mainly flood-plains covered by farmlands and urbanised. Because of their low permeability and their range, mountain areas contribute greatly to the formation of flood flows, which are principally generated by infiltration excess run-off (Brath *et al.*, 2006). For a detailed description of the Reno river basin, please refer to Brath *et al.* (2003), Castellarin (2007), Castellarin *et al.* (2009) and Di Prinzio *et al.* (2011). Extreme rainfall data consisting of a series of annual maxima (with durations equal to 15 min and 30 min, 1 h, 3 h, 6 h, 12 h, and 24 h, and 1 day) observed in the period 1935–1989 in a dense network of rain gauges managed by the National Hydrographical Service of Italy were analysed. IDF curves for different return periods (T_r) were determined according to Di Baldassarre *et al.* (2006), while maximum yearly peak discharge values are available from 1938 to 2010. A DEM at 20-m resolution was provided by IGMI (Italian Geographic Military Institute) (2003), and land cover data were retrieved from the CORINE (Coordination of Information on Environment) Database (2000) website.

For all of the selected case studies, the hypothesis of stationarity of climate and land use condition is assumed, and an empirical relationship between return period (T_r) and yearly maxima peak discharge Q_p was determined by employing the empirical cumulative distribution function according to the Weibull formula:

$$\frac{j}{n+1}=1-\frac{1}{T_r} \quad (7)$$

where $j = 1,. n$ denotes the j^{th} observation of the samples arranged in ascending order.

Figure 1 shows the locations of the selected watersheds, while in Table 1, a summary of their main characteristics is reported; in Figure 2, DEMs and the land cover maps for each case study area are shown in detail. The average CN value, which is necessary for rainfall excess estimations as described in the previous section, was quantified through empirical evaluation using look-up tables (Chow *et al.*, 1988; Natural Resources Conservation Service (NRCS), 2008), while the basin concentration time (T_c) was estimated using the Natural Resources Conservation Service (NRCS) (1997) method, selected from among the several formulas available in the literature (Grimaldi *et al.*, 2012a).

Figure 1 Locations of the selected watersheds.

EBA4SUB framework analysis

Two different analyses were performed: the first on a single watershed, the Orgeval basin, aiming to investigate the role of the Chicago hyetograph peak position and time discretisation, and the second on all five watersheds, aiming to provide a comparison between the observed and simulated peak discharges related to return period values.

Chicago peak position and time resolution

As described in 'EBA4SUB framework' Section, the Chicago equation allows the user to hypothesise where the peak position is located in the design hyetograph. This choice, of course, could influence the estimation of the peak discharge value, because if the intensity peak is positioned at the beginning of the gross rainfall event, it could be affected by the initial abstraction from the SCS-CN, while if the peak is located at the end of the event, it could be almost fully preserved. Generally speaking, $r_c < 0.5$ and $r_c > 0.5$ can be viewed as a 'lucky' and 'unlucky' situation, respectively; indeed, in the latter the extreme rainfall amount is distributed over time in a unfavourable condition ($r_c > 0.5$). In an empirical framework such as EBA4SUB, assuming $r_c = 0.5$ could represent a satisfactory compromise that is commonly adopted without increasing the subjectivity of the application; indeed, the results are related to a specific hypothesis that can be reproduced. However, it is useful to verify the sensitivity of this arbitrary choice.

For the Orgeval watershed, the Chicago hyetographs related to return periods of 2 and 20 years, with r_c ranging from 0 to 1 and a time resolution of 15 min, were estimated and are shown in Figure 3. The two panels in Figure 3 reveal similar behaviour: for high return periods, CN4GA seems insensitive to the position of the peak inside the gross hyetograph and is always able to preserve the position of the

Table 1 Main characteristics of case study watersheds and observed data

Basin	Ilme	Sieber	Boehme	Orgeval	Samoggia
Location	Germany	Germany	Germany	France	Italy
Outlet coordinate N (m)	5 740 613	5 728 728	5 859 861	2 425 657	4 934 912
Outlet coordinate E (m)	552 027	598 976	550 411	656 976	668 635
Reference system	UTM32N	UTM32N	UTM32N	NTF Lambert II	UTM32N
Area (km^2)	148.4	44.2	285.7	106.1	178.5
Min elevation (m)	117	338	18	79	51
Average elevation (m)	338	644	81	156	380
Maximum elevation (m)	580	936	170	191	1629
Average basin slope (%)	16.8	31.4	6.6	1.9	19.1
Main channel length (km)	26.4	16.9	35.3	13.1	39.7
Average CN value (-)	65.8	61.7	70.7	76.5	74.4
T_c (h)	7.2	4.2	12.3	10.3	7.4
Rainfall available data	IDF	IDF	IDF	41 years	IDF
Discharge available data	55 years	45 years	46 years	41 years	41 years

IDF, intensity-duration-frequency; CN, curve number.

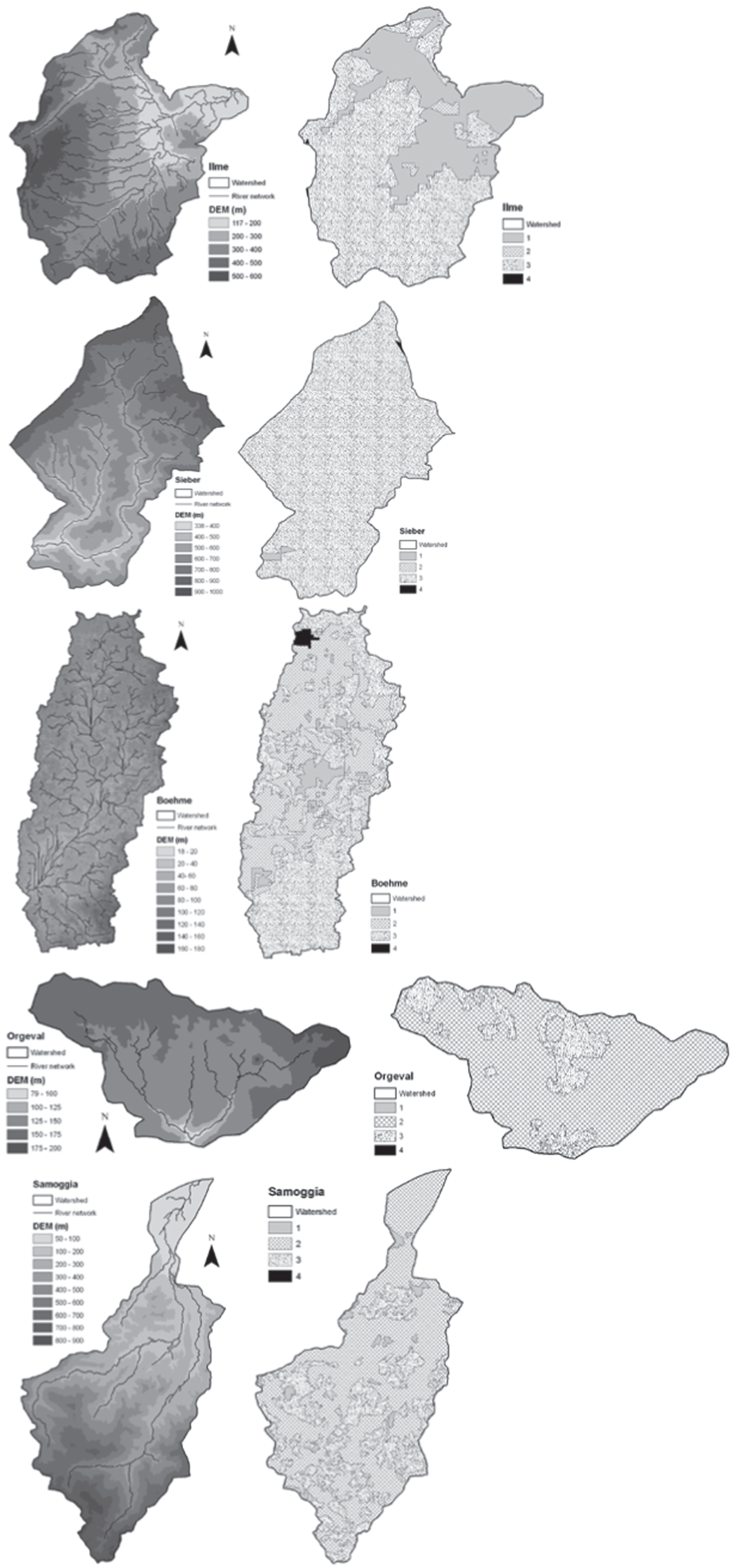

Figure 2 Case study digital elevation models (DEM) (left) and land cover maps (right; 1: artificial surfaces; 2: agricultural areas; 3: forests and semi-natural areas; 4: wetlands).

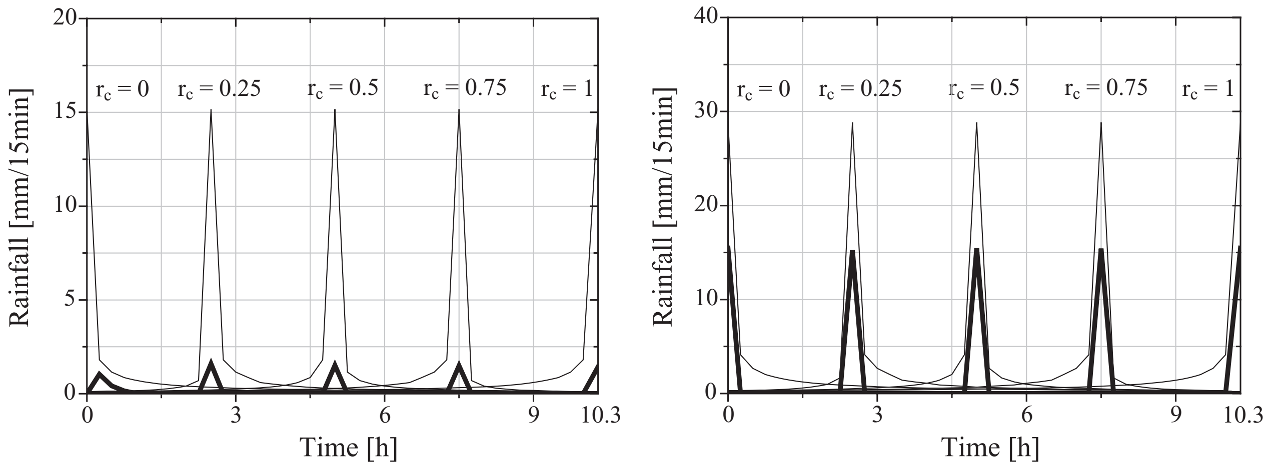

Figure 3 Gross (thin line) and net (thick line) Chicago hyetographs using r_c from 0 to 1 for T_r equal to 2 (left) and 20 years (right).

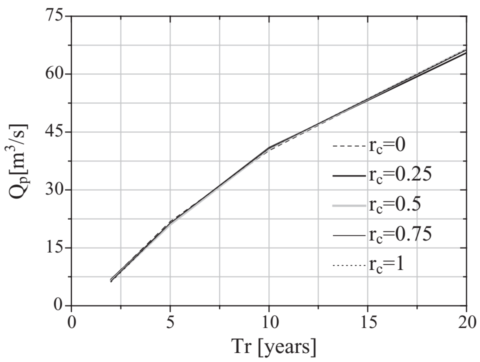

Figure 4 Comparison among estimated peak discharges for different return periods and r_c values.

net rainfall peak within the gross hyetograph. For low return periods, when cumulative gross rainfall depths are moderate, CN4GA is still able to preserve the position of the net rainfall peak within the gross hyetograph, except when $r_c = 0$, when the role of I_a, as previously specified, affects the net rainfall estimation. Indeed, for $T_r = 2$ years, the net rainfall peak has a value of 1.04 mm/15 min for $r_c = 0$ and a value of 1.5 mm/15 min for the other r_c values. This happens because with $r_c = 0$, the initial abstraction affects the first part of the gross rainfall hyetograph where the peak is present, and in doing so reduces the first part of the net rainfall hyetograph. Regardless, because the cumulative net rainfall value is related to the CN value and is therefore the same for all the considered hyetographs, the net hyetograph for $r_c = 0$ has a longer duration with respect to the other r_c values, as it is constrained to distribute the same net rainfall depth over time.

Figure 4 shows the peak discharge values estimated by varying the return periods and r_c. The five lines appear to be indistinguishable, confirming that in the EBA4SUB framework, r_c has no significant role in the final estimation of peak discharge. Our opinion concerning this result is that the slope of IDF is low and consequently the curvature of the Chicago hyetograph is very high. As a consequence, the gross rainfall intensity related to a duration of 15 min is so high that the residual rainfall amount distributed over time has a too small intensity to influence the final results.

The other important issue that could represent a source of subjectivity is the choice of the time resolution in the EBA4SUB application. Indeed, the choice of the Chicago hyetograph means that depending on whether the user refers to a 5-min or 1-h resolution, the peak rainfall intensity would be different compared to the IDF curve. The expected behaviour is that the peak discharge would be higher for a shorter time resolution: this could happen because when using a small time step (i.e. a short time resolution, e.g. 15 min), the IDF shape provides a high rainfall intensity, and if the basin response is highly impulsive, the logical consequence would be a high peak discharge; conversely, when using a longer time resolution, e.g. 60 min, a lower rainfall intensity and consequently a lower peak discharge are expected. However, such circumstances could be limited because the convolution between IUH and rainfall data reduces the expected amplification of the peak discharge: indeed, choosing a shorter or longer resolution time not only causes an effect on the hyetograph in terms of peak intensity but also on the IUH shape. The IUH frequencies will be smaller for shorter resolution times, and thus the greater impulse will be convoluted by lower IUH values.

To quantify the expected results for the described analysis in the Orgeval watershed, the following time resolutions were adopted to estimate the peak discharge: 15 min, 30 min and 60 min. Figure 5 shows the gross rainfall hyetographs for a return period of 20 years and the corresponding WFIUHs: it is clear that a shorter time resolution affects the

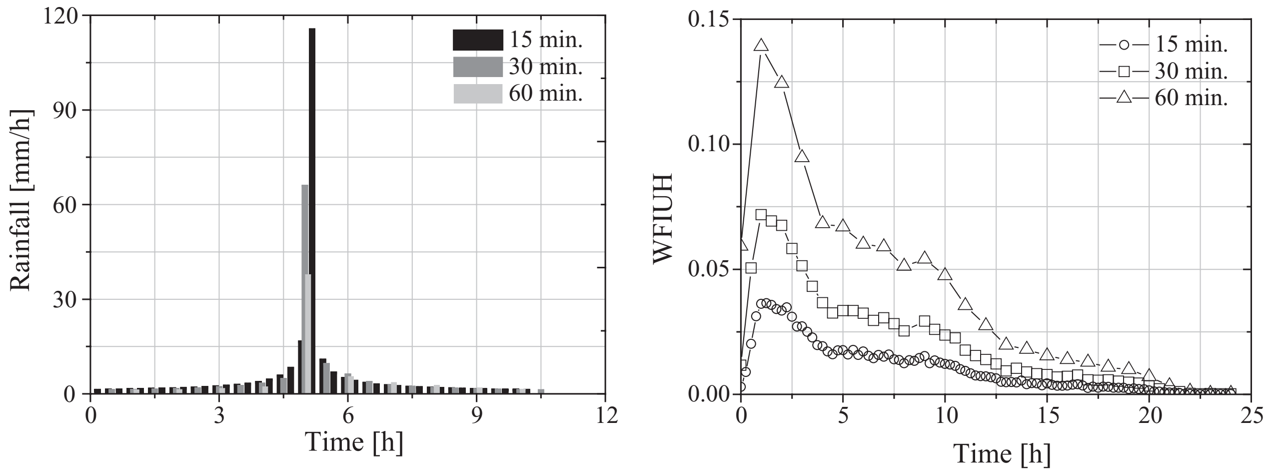

Figure 5 Hyetographs (left; $T_r = 20$ years, $r_c = 0.5$) and width function instantaneous unit hydrographs (WFIUHs) (right) at different time resolutions.

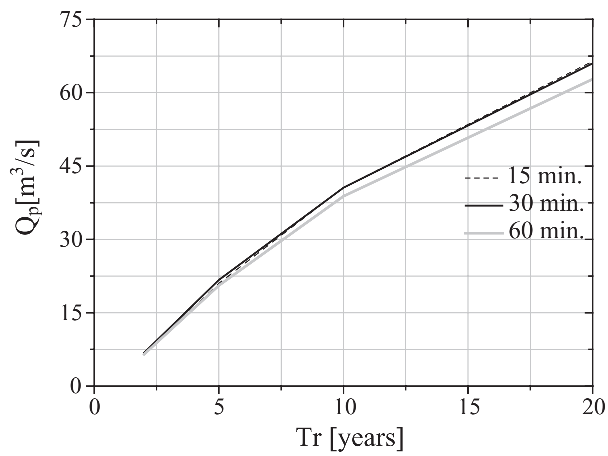

Figure 6 Comparison among estimated peak discharges for different return periods and resolution times.

hyetograph peak and reduces the IUH frequencies. For instance, the gross rainfall peak intensities are 115 mm/h at a 15-min time resolution, 65.8 mm/h at a 30-min time resolution and 37.7 mm/h at a 60-min resolution, while the IUH peaks are 0.035, 0.059 and 0.139, respectively.

Figure 6 shows the differences among the peak discharges for return periods of 2, 5, 10, and 20 years and for the adopted time resolutions. The results confirm that the differences are limited and that the resolution time is not a significant source of subjectivity. However, although differences are limited, it was confirmed that higher peak discharges result from a shorter time resolution, as expected: peak discharge values for a return period of 20 years are 66.43 m^3/s for a 15-min time resolution, 66.02 m^3/s for a 30-min time resolution and 62.79 m^3/s for a 60-min time resolution.

On the basis of the described results, the practitioner is recommended to refer to the 60-min resolution for hyetograph construction, because 60 min is the observed rainfall value on which the IDF is usually built, which means that a limited bias on the results may be expected. At the same time, it is useful to mention that a short time resolution is important for preserving the IUH shape provided by the watershed topography information as much as possible. Because the WFIUH base time is related to the concentration time, in the case of small basins where the T_c is usually less than 10 h, adopting a time resolution of 60 min would yield an IUH shaped by only a few points. This difference is highlighted in Figure 4, where it can be noted that at a 60-min time resolution, the WFIUH shape is smoother with respect to that given for a 15-min time resolution. Hence, to best use the geomorphological information provided by the width function framework, a time resolution of 15 min or less is suggested for IUH determination. Obviously, because both the rainfall data and the IUH data must have the same time resolution in the discretisation of the convolution integral, we suggest simply transforming the hyetograph discretisation from 60 min to 15 min, adopting constant rainfall intensity values in the four subhourly fractions, in doing so best maintaining the detailed information provided by WFIUH and avoiding bias in the determination of rainfall intensity.

Finally, another potential user choice is avoided when choosing a 60-min time resolution in hyetograph discretisation: the modeler could adopt a simple IDF curve with two parameters or a more complex IDF representation described by three parameters. However, this difference makes sense mainly when the rainfall resolution is shorter than 60 min, ranging down to 5 min. Indeed, the third IDF parameter allows a better fit to the empirical rainfall data in particular for storms presenting durations shorter than 1 h when there is a change in the curvature in the IDF. Employing a 60-min time resolution, the additional parameter does not add useful information, and the user can safely refer to the simpler two-parameter IDF.

Evaluation of EBA4SUB comparing observed and simulated peak discharges

As previously mentioned, in this section, a preliminary performance evaluation of EBA4SUB is provided. Specifically, because observed yearly peak discharge maxima are available for all five watersheds for an appropriate number of years, it is possible to compare observed return-time-dependent peaks to the values provided by the EBA4SUB application.

The following return periods are considered in the comparison: 2, 5, 10, and 20 years; we limit the return period to 20 years because the maximum sample length is approximately 40 years.

Considering the results obtained in the previous section, for all the case studies, we adopted a time resolution of 60 min for the Chicago hyetograph and 15 min for the WFIUH. The design hyetograph was subsequently discretised at a 15-min time resolution, adopting constant values in the subhourly steps. CN4GA was applied to the gross rainfall hyetographs, and the resulting net rainfall scenarios were convolved with the corresponding WFIUHs, allowing the comparison of modelled and observed peak discharges.

In Figure 7, the gross and net rainfall design hyetographs are reported for all the watersheds. Among the German case studies, the Sieber basin is the smallest, and because it presents a small concentration time (4.2 h), the cumulative gross rainfall is low (66 mm for 20 years' return period), while the gross rainfall peak intensity is relevant (55 mm/h for 20 years' return period). Given that the basin is quite permeable and forested (CN is 61.7), the losses are predominant and, consequently, the net cumulative rainfall and net rainfall peak intensity are low (5.9 mm and 12.3 mm/h, respectively, for 20 years' return period).

Conversely, the Boehme basin is the largest; however, even though it shows a higher concentration time (12.3 h), the cumulative gross rainfall is less than the corresponding value for the Sieber basin (62 mm for 20 years' return period), due to the effect of the ARF factor (0.97 for the Sieber basin, 0.91 for the Boehme basin) and a flatter IDF curve (the coefficient n in the IDF curve is 0.25 for Boehme and 0.29 for Sieber). Moreover, the Boehme watershed is less forested and permeable than the Sieber basin (CN is 70.7), leading to a greater net cumulative rainfall and net rainfall peak intensity (11.3 mm and 14.9 mm/h, respectively, for 20 years' return period).

Concerning the French case study, the Orgeval watershed is characterised by a concentration time equal to 10.3 h that, referring to a return period of 20 years, leads to a cumulative gross rainfall equal to 58.7 mm and to a gross rainfall peak intensity equal to 37.7 mm/h, due mainly to a particularly flat IDF (n coefficient is 0.19). However, because the Orgeval basin is the least permeable among the considered case studies (CN is 76.5), it yields a net cumulative rainfall of 15.3 mm and a net rainfall peak intensity equal to 20.1 mm/h, i.e. greater than in the German case studies.

Finally, the Italian watershed is characterised by a concentration time equal to 7.4 h and a steeper IDF curvature (the coefficient n in the IDF curve is 0.33), leading to a cumulative gross rainfall equal to 84.1 mm and a gross rainfall peak intensity equal to 43.7 mm/h. Given that the basin is also characterised by a moderate impermeable soil (CN is 74.4), CN4GA provides a net cumulative rainfall of 28.8 mm and a net rainfall peak intensity equal to 30.4 mm/h, i.e. the highest values among the considered watersheds.

Figure 8 shows the watersheds' WFIUHs. As previously mentioned, an hourly resolution is unable to accurately represent the topographic information for the basins characterised by small concentration times, leading to a smoother unit hydrograph; this is emphasised in particular when high resolution digital elevation data (e.g. Lidar) are available (Petroselli, 2012). Adopting a 60-min time resolution instead of 15 min would reduce the number of points (by a factor of four), causing a loss of information for the basins characterised by a WFIUH presenting multiple peaks, such as Sieber and Boehme.

Finally, in Figure 9, a comparison between observed and simulated peak discharge values is provided for all five case studies and for the considered return periods. The results depicted in Figure 9 suggest some comments. First, it is confirmed that is difficult for an empirical approach to provide values similar to the observed ones: for instance, for a return period equal to 20 years, differences between observed and modelled peak discharges are 64.7% for the Ilme basin (39.4 m^3/s compared to 64.9 m^3/s), 39.3% for the Sieber basin (36.5 m^3/s compared to 22.1 m^3/s), 165% for the Boehme basin (30.4 m^3/s compared to 80.7 m^3/s), 112% for the Orgeval basin (30.5 m^3/s compared to 64.8 m^3/s) and 19% for the Samoggia basin (444 m^3/s compared to 352 m^3/s). This is due to several factors; indeed, each step of the proposed procedure assumes some hypotheses that may be very different from the real behaviour. The critical rainfall concept, while realistic and reasonable, is far from the storm that determined the event related to the specific return period. Furthermore, as in the case of Samoggia watershed, the IDF curves are regional extrapolations of rain gauge information and consequently rely on significant approximations. Moreover, the SCS-CN approach for net rainfall calculation is an empirical scheme that was calibrated in the

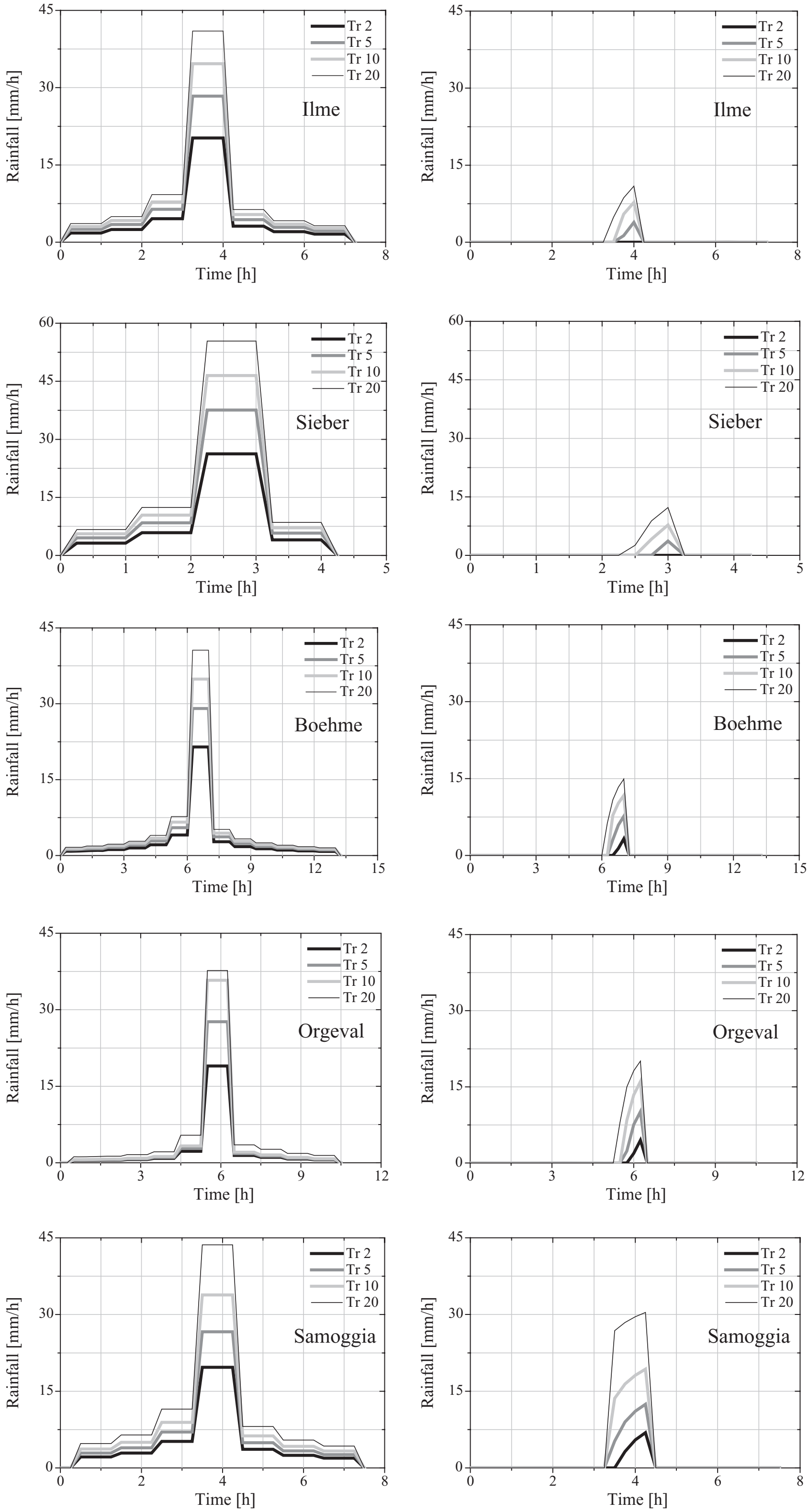

Figure 7 Design gross (left) and net (right) hyetographs related to return periods for the five case studies at a 60-min time resolution, further discretised at 15-min increments by adopting a constant rainfall intensity in the subhourly steps.

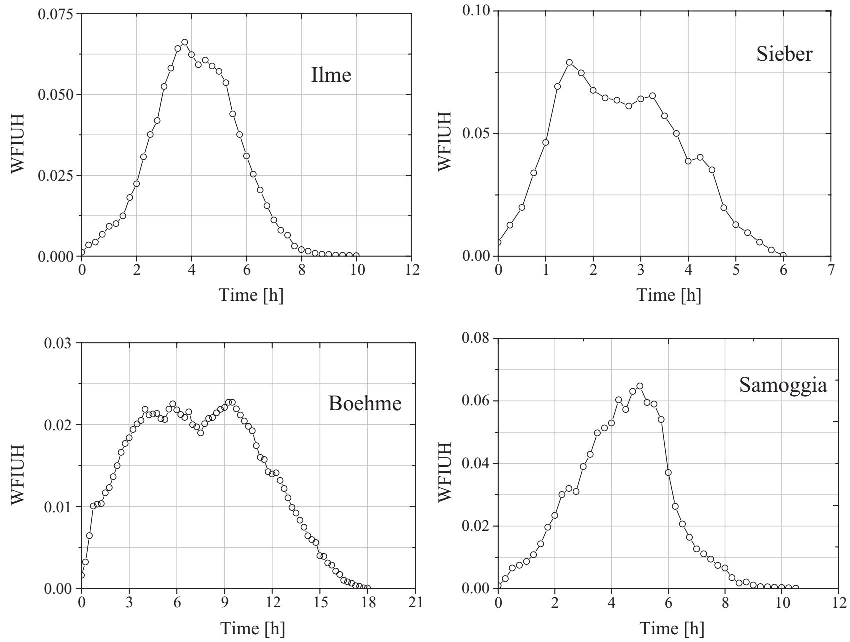

Figure 8 Width function instantaneous unit hydrograph (WFIUH) for the Ilme, Sieber, Boehme, and Samoggia watersheds (the Orgeval WFIUH is shown in Figure 5).

United States, so significant differences in Europe can be expected, and in any case, it is not accurate as we would need to have similar observed values.

Second, looking at Figure 9, in particular for the Ilme, Boehme and Orgeval watersheds, a tendency may be observed for the Chicago hyetograph to overestimate the peak discharge for high return periods, as a consequence of the critical rainfall peak, and to underestimate the peak discharge for low return periods, as a consequence of the initial abstraction value of the SCS-CN approach that influences the net hyetographs. This circumstance does not occur for the Sieber and Samoggia case studies.

Regarding the Samoggia case study, it seems to provide the best results, most likely because it is characterised by Hortonian run-off behaviour, coherent to the EBA4SUB framework.

It is apparent that the differences shown in Figure 9 are relevant; however, while this was expected, the results are comparable to similar studies available in the literature that employ more sophisticated and complex hydrological models. For instance, in Calver *et al.* (2009), 107 Great Britain watersheds were analysed, employing the flood peak and event-based methods given in the Flood Estimation Handbook (Institute of Hydrology, 1999), and the mean absolute percentage error estimated for the predicted and observed 50-year return period flood-peak values was 40% (Calver *et al.*, 2009, p. 28: Table 1). In Moretti and Montanari (2008), a spatially distributed rainfall run-off model was applied in a watershed with an area of 1294 km^2, and for a 50-year return period, the difference between the observed and modelled peak discharge was approximately 40% (Moretti and Montanari, 2008, p. 1149: Figure 6). In Haberlandt *et al.* (2008), simulations performed using the alternating renewal model and the HEC-HMS model calibrated with the observed data showed a difference in the peak flow of up to 50% for a 50-year return period [Haberlandt *et al.*, 2008, p. 1364: Figure 10(a)]. In Viviroli *et al.* (2009), the continuous distributed PREVAH model was applied to a large number of watersheds, and the differences between the calculated and observed 100-year return period peak flow values varied from −75% to 200% (Viviroli *et al.*, 2009, p. 215; Figure 5).

Finally, it is important to remember that this approach is designed for providing a surface run-off estimation, so the subsurface component of discharge is not considered. This is important because not all the considered watersheds are characterised by small or null subsurface components, which could be an additional explanation for the underestimation of the peak discharge for lower return periods; however, because the framework is designed for small and ungauged basins and to estimate the design peak discharge, we expect that this aspect is less important for high return periods for which the subsurface component has a limited role.

Conclusions

In the present work, a preliminary evaluation of the EBA4SUB framework is described. This procedure was

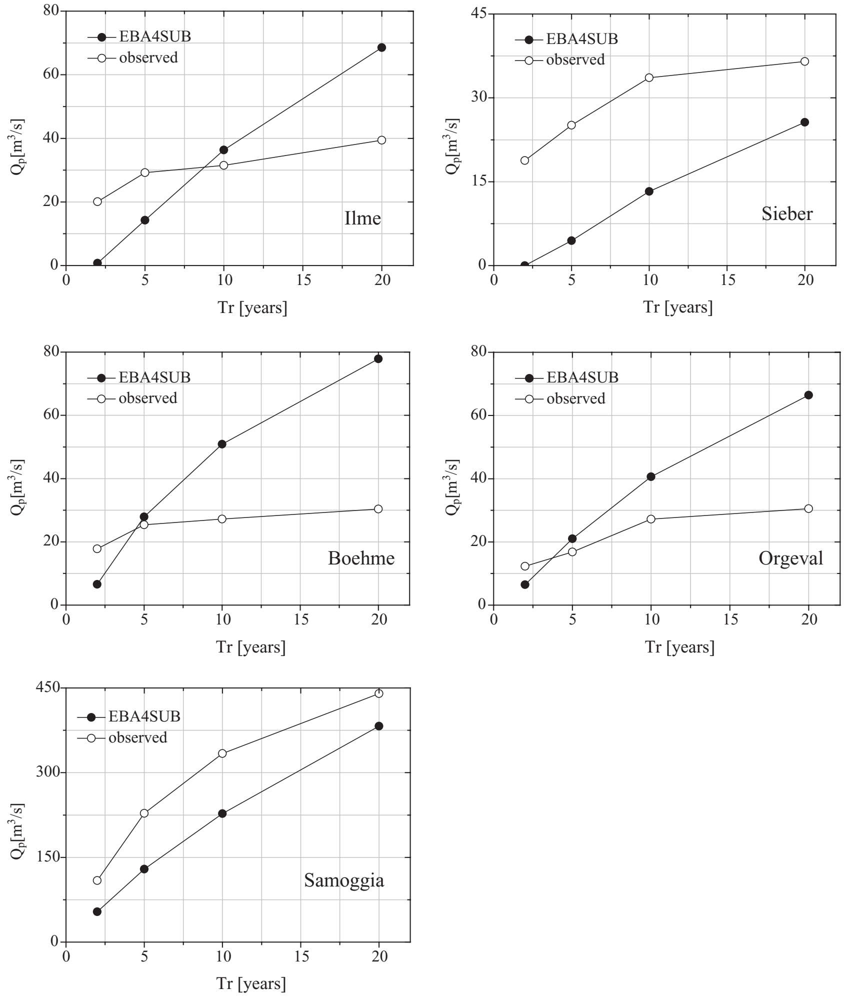

Figure 9 Comparison between observed and simulated discharge in the five case studies.

recently introduced to propose an alternative method to the rational formula for estimating design hydrographs in small and ungauged basins located in areas lacking regionalisation analyses, forcing the hydrologist to adopt empirical formulas. EBA4SUB is characterised by several steps, including design hyetograph estimation, net rainfall analysis and rainfall-run-off transformation. All of the modules included in EBA4SUB are based on common methods available in the literature, which have been appropriately modified and updated to be applied using the same simple data input necessary for the rational formula. The key elements are the Chicago hyetograph, the curve number for the Green-Ampt (CN4GA) method, and the width function instantaneous unit hydrograph built with only one parameter (WFIUH-1par).

Five small watersheds located in Europe were selected as case studies and analysed in detail to investigate two aspects: the uncertainty related to the choice of the peak position in the Chicago design hyetograph and the uncertainty resulting from the time resolution of the entire model. Furthermore, a comparison between the observed and simulated peak discharge related to several return periods was provided.

The obtained results suggest that varying the peak position and the time resolution does not significantly affect the results, so their presence in the framework does not increase the subjectivity of the EBA4SUB application. Indeed, it was verified that selecting different r_c values, similar net rainfall peaks are obtained. The reason of that is due to the low IDF n parameter that gives to the peak values a dominant behaviour compared to the residual amount of rainfall distributed over the time. Concerning the time resolution, the limited variability is due to a compensation effect with the WFIUH; when reducing the time resolution the net rainfall intensity increases while the WFIUH frequency decreases so the resulting rainfall-run-off convolution compensates for the effects showing a limited results variability.

Comparison between the observed and simulated peak discharge values shows relevant differences. This result was expected considering the challenging application. However, the error percentages are in line with common values present in literature related to similar applications performed with more complex and sophisticated models calibrated on observed data. This is encouraging considering that EBA4SUB is applied without calibration and with simple modules widely used in practical hydrology.

Future research is necessary and planned for generalising the obtained results extending the validation to a larger number of watersheds, specifically in the Mediterranean area where usually basins are lacking of information, and varying the watershed class in terms of arid condition. Moreover, comparison tests with frameworks that need calibration or with approaches based on regionalisation procedures are subject of ongoing work. This could be useful to verify if the proposed model is able to provide similar results and hence if it could be a good candidate for estimating hydrograph design for small basins not included in areas hydrologically similar to gauged ones.

In conclusion, EBA4SUB appears to be promising above all concerning the reduced subjectivity present in its implementation, which in our opinion is a key issue in practical empirical hydrology.

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