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# An evidence for enhancing the design hydrograph estimation for small and ungauged basins in Ethiopia

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ABSTRACT

*Study region:* Ethiopia and Upper Blue Nile Basin.
*Study focus:* Estimating design hydrograph characteristics (e.g. flood peak discharge, volume and duration) is a crucial topic in hydrology and this is particularly challenging in data scarce regions. In recent years, significant innovations in hydrological modeling were introduced, allowing for more advanced analyses also in ungauged areas, in doing so limiting the application of empirical approaches (e.g. the rational formula). In the present work we summarize the current practice in Ethiopia and explore the possibility to apply a simplified continuous modeling for estimating design hydrographs.
*New hydrological insights for the region:* This study supports the conclusion that COSMO4SUB (Continuous Simulation Model for Small and Ungauged Basins) framework, a simplified continuous rainfall-runoff model specifically tailored for small and ungauged basins, can be applied in Ethiopia. Indeed, the minimal information available in the country are sufficient for applying such modeling approach, that can provide useful outputs for a variety of practical hydrological studies.

## 1. Introduction

One of the common aims in hydrological studies is estimating design hydrograph characteristics (e.g. peak discharge, flood volume, hydrograph shape, duration, presence of multiple peaks) for a selected watershed. Such information is crucial for a variety of practical applications and environmental studies (e.g. for designing hydraulic infrastructures or producing flood hazard maps). In the last century, the rapid evolution in rainfall-runoff models made available to practitioners a paramount of simple (e.g. rational formula or event-based models) or elaborated (e.g. continuous or distributed models) approaches. Typically, the adopted choice is a compromise among the relevance of the study, the economic resources, and the availability of observations (Młyński et al., 2019) .

Recently, it was emphasized the benefit of continuous modeling compared to the event-based approach (Boughton and Droop, 2003; De Luca et al., 2022). The latter is usually based on a lumped model providing as output a design hydrograph with an assigned

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**Table 1**
Summary of the meteorological stations. Region, class station, total and active number of stations, average number of years of observations (AYO).

| Number | Region | C1 | C2 | C3 | C4 | Total | Active | AYO (C1–C2) | AYO (C3–C4) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Addis Ababa | 2 | 0 | 2 | 1 | 5 | 5 | 72 | 38 |
| 2 | Afar | 8 | 0 | 17 | 7 | 32 | 30 | 35 | 29 |
| 3 | Amhara | 39 | 2 | 93 | 108 | 242 | 232 | 44 | 34 |
| 4 | Benishangul-Gumuz | 6 | 0 | 11 | 9 | 26 | 26 | 41 | 29 |
| 5 | Dire Dawa | 1 | 0 | 0 | 0 | 1 | 1 | – | – |
| 6 | Gambella | 3 | 0 | 5 | 6 | 14 | 13 | 34 | 38 |
| 7 | Harari | 1 | 0 | 2 | 1 | 4 | 4 | 41 | 24 |
| 8 | Oromia | 61 | 1 | 136 | 159 | 357 | 341 | 48 | 41 |
| 9 | SNNPR | 20 | 0 | 53 | 65 | 138 | 133 | 42 | 38 |
| 10 | Somali | 11 | 0 | 19 | 9 | 39 | 39 | 25 | 35 |
| 11 | Tigray | 15 | 0 | 25 | 21 | 61 | 60 | 44 | 30 |
| | **Total** | **167** | **3** | **363** | **386** | **919** | **884** | **44** | **37** |

return period, while the former is based on a lumped or distributed model providing as output a design simulation (e.g. a simulated runoff time series). The main difference between the two approaches is the rainfall input: indeed, the event-based approach refers to a design storm while the continuous one refers to a long synthetic rainfall scenario. In practice, the benefit of the continuous modeling consists in a more realistic estimation of hydrograph volumes and in providing a simulated runoff time series that allows for a multitude of applications: a) direct use of synthetic runoff time series (Grimaldi et al., 2013a; Sikorska et al., 2018); b) flood frequency analysis for estimating peak discharge (De Paola et al., 2018); c) design hydrograph estimation with multivariate approach (Serinaldi and Grimaldi, 2011; Brunner et al., 2017); d) Monte Carlo analysis with the synthetic runoff time series (Annis et al., 2020).

While this promising approach is widely diffused and applied (Boughton and Droop, 2003; Berthet et al., 2009; Beneyto et al., 2020; Brown et al., 2022), it still needs some ameliorations, mainly related to the synthetic rainfall generation. However, we can consider it as a well-established methodology that, probably, will commonly be adopted in the future and will substitute the event-based approach.

In the last years, simplified versions of continuous modeling were implemented for small (i.e. with a contributing area smaller than few hundreds of km$^2$) and ungauged (i.e. lacking of runoff observations) basins, demonstrating that also in such challenging conditions the continuous framework can provide an added value to the practitioners (Grimaldi et al., 2012a, 2013a, 2021). The challenge of such approach concerns its application using the same minimal input information typically used when employing the rational formula.

In this work we investigate the possibility to apply a specific and simplified continuous framework (COSMO4SUB – Continuous Simulation Model for Small and Ungauged basins, Grimaldi et al., 2012a, 2021) in selected Ethiopian watersheds, verifying if this model can improve the hydrologic-hydraulic design procedure and overcome the diffused application of the rational formula. Indeed, it is well known in literature (e.g. Grimaldi and Petroselli, 2014) that the rational formula, although is a useful and widely used method, presents severe limitations and provides minimal output information (i.e. only the peak discharge). However, in Ethiopia, the rational formula is commonly adopted, due to its simplicity, although in some areas of the country it seems that there are enough observations for applying more advanced models. For instance, distributed rainfall-runoff models like SWAT, HEC-HMS, or HBV have been successfully applied (Desta and Lemma, 2017; Worqlul et al., 2018; Zelelew and Melesse, 2018; Goshime et al., 2019; Leta et al., 2021). It is noteworthy that, in all the aforementioned applications, the rainfall input data set was always available only at daily scale and not with finer temporal resolution, while other input data such as digital elevation model, land use and soil type information were available at appropriate resolution. Based on this, it seems that the rainfall observation is a potential bottleneck for implementing continuous schemes, often characterized by the use of rainfall timeseries at higher (e.g. hourly) resolution.

This manuscript aims, hence, in answering the following questions:

- What is the common procedure applied in Ethiopia for estimating design hydrograph characteristics (peak discharge, flood volume, flood duration) and what are the available data for the practitioners?
- Is it possible to apply the COSMO4SUB model as an alternative to the rational formula and to the event-based approach?

In order to answer these questions, we provide an overview of the hydrological procedures adopted in Ethiopia and the related data availability (Section 2). Then, the rational formula, an event-based approach (EBA4SUB – Event Based Approach for small and ungauged basins) and the COSMO4SUB model are applied and compared on four case studies (Sections 3 and 4). In Section 5 results are illustrated and commented supporting the conclusions available in Section 6.

## 2. Hydrological data availability and design procedure in Ethiopia

Ethiopia is a Federal Democratic Republic composed by 9 National Regional States (NRS), i.e. “Amhara”, “Tigray”, “Afar”, “Oromia”, “Somali”, “Benishangul-Gumuz”, “Southern Nations, Nationalities and Peoples Region (SNNPR)”, “Gambella” and “Harari”, and two administrative councils, i.e. “Addis Ababa” and “Dire Dawa”. In Ethiopia, the official authority for meteorological observation is the National Meteorology Agency (NMA) (http://www.ethiomet.gov.et/), that was established in 1980 although since 1946 some preliminary meteorological tasks were carried out by government offices, mainly in the agricultural sector.

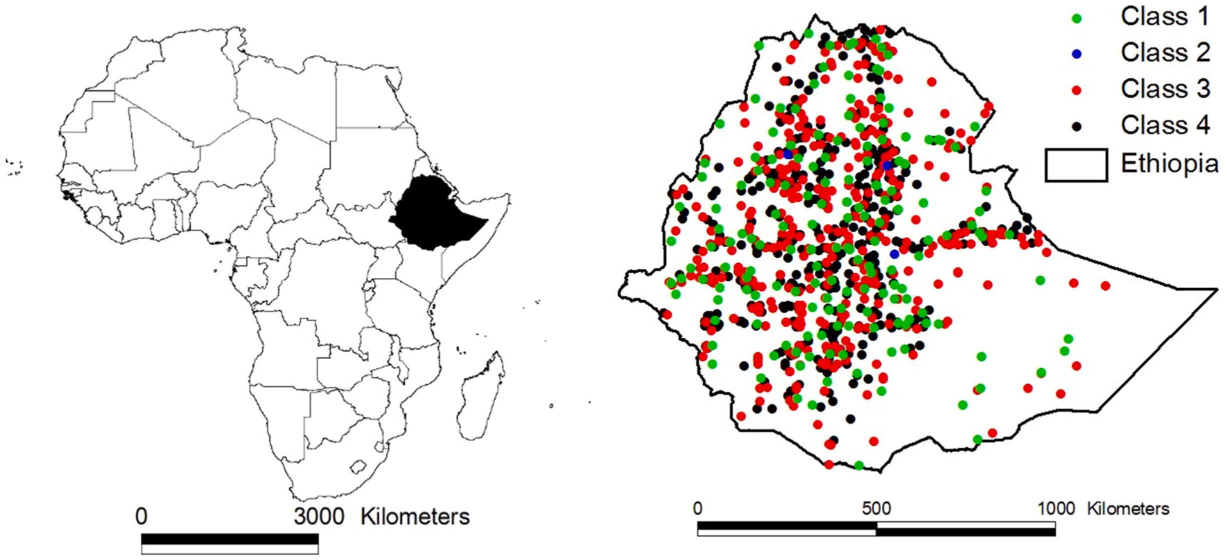


**Fig. 1.** Geographical raingauge distribution in Ethiopia.

Regional meteorological stations have been classified by NMA as first class (C1), second class (C2), third class (C3) and fourth class (C4) stations. C1 stations are "synoptic stations" and provide hourly observations (e.g. rainfall, air and soil temperature, wind, evaporation). C2 stations are "principal or indicative stations" and provide observations every three hours. C3 stations are "ordinary stations" where only three meteorological elements are observed (maximum air temperature of the day, minimum air temperature of the day and total rainfall amount). C4 stations are "rainfall recording stations" where only the daily total rainfall amount is observed. In Table 1 a resume of meteorological stations is reported. As it can be seen from Table 1, in Ethiopia there are 919 meteorological stations (884 listed as active) and 167 (18.9 % of the total active) are classified as C1, i.e. recording hourly cumulated rainfall. The average number of years of observations is equal to 44 for stations C1–C2 and to 37 for stations C3–C4, confirming that large areas have only few years of data available (Tamalew and Kemal, 2016).

Regarding the spatial location of the meteorological stations (Fig. 1), they are not regularly distributed throughout the country, and in some large areas of the country (e.g. Afar and Somali) there are only few ones. This circumstance confirms that the lack of meteorological data is one of the major problems when dealing with hydrological and hydraulic applications (Gebreigziabher, 2020).

Indeed, design hydrograph estimation for small and ungauged basins is a critical issue and reliable estimates of flood frequency in terms of peak flows and volumes remain a current challenge in developing countries like Ethiopia (Gebremedhin, 2017). Moreover, in water resources planning and in rainfall-runoff relationship studies, the accurate estimation of basin hydrologic response is the main concern of Ethiopian hydrologists. As a consequence, such research topic has been very active in Ethiopia, and the Ethiopian Ministry of Water, Irrigation and Energy (MoWIE) Research and Development Directorate identified that most of the rivers in the country are ungauged, suggesting the development of improved tools and methods to estimate the design discharge of ungauged rivers.

From a scientific point of view, recent literature shows a growing interest in using advanced hydraulic and hydrologic models in Ethiopia. Erena et al. (2018) employed the distributed FLO-2D hydrodynamic model to identify flood prone villages, but the availability of rainfall records obtained from the investigated meteorological stations was limited to daily scale, making necessary the application of a rainfall disaggregation model. Chimdessa et al. (2019) assessed the impact of land use and land cover (LULC) change on the Didessa river flow and soil loss using SWAT model under historical and future climates, employing LULC of the years 1986, 2001 and 2015 that were independently combined with the historical climate to assess their individual impacts on river flow and soil loss. Adem et al. (2020) investigated the hydrologic response of two watersheds in the headwaters of the Blue Nile using three different digital soil inventories and the widely used SWAT model. Dibaba et al. (2020) used first Cellular Automata (CA)-Markov in IDRISI software to predict the future LULC scenarios and the ensemble mean of four regional climate models, and then the SWAT model to evaluate the watershed hydrological responses under separate and combined LULC and climate change.

From the practitioner point of view, the rational formula is probably the most commonly used method to estimate the peak discharge in Ethiopia, employing rainfall data synthesized in the Depth-Duration-Frequency (DDF) curves. For instance, Erena and Worku (2019) analyzed the dynamics of LULC and resulting surface runoff management for environmental flood hazard mitigation in case of Dire Dawa city. The study was aimed to explore the hydrological impacts of LULC changes using the rational method and four decade based satellite imagery analyzed employing ERDAS imagine. Moreover, the Ethiopia Road Authority suggests the rational formula to estimate the peak flow to construct ditches, canals and other different drainage structures.

For applying the rational formula, the DDF curves are necessary; however, in the case of Ethiopia, the amount of available rainfall data at high time resolution was too sparse for developing accurate DDF curves and was insufficient to develop a frequency distribution plot for each rainfall period (ERA, 2013; Zimale and Beyene, 2017). Therefore, the Ethiopian Road Authority (ERA) developed DDF curves based on the disaggregation of the 24-h rainfall using several methods, verifying their validity with short-duration rainfall

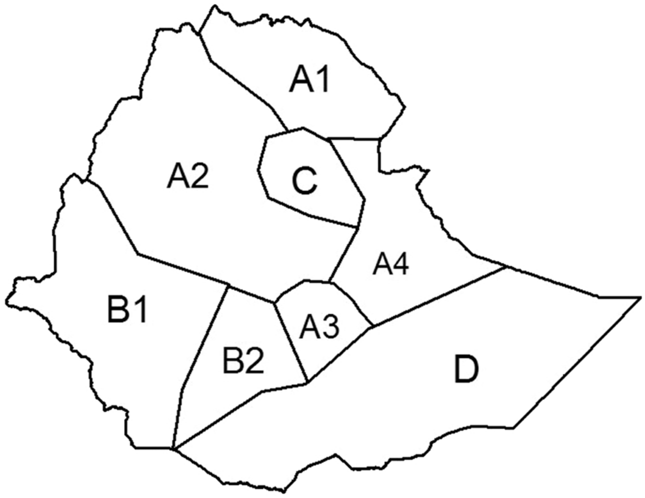


**Fig. 2.** Ethiopian homogeneous rainfall regions.

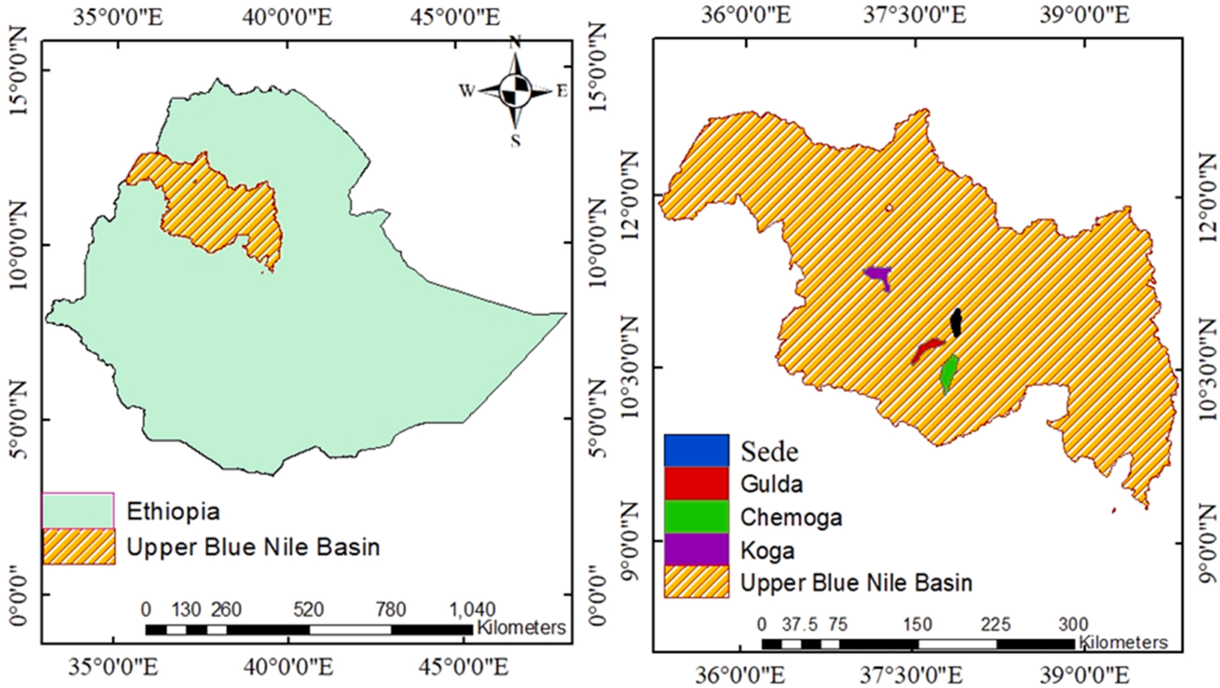


**Fig. 3.** Localization of the four case study watersheds.

where available. The DDF relationship curves are highly refereed material for the design of hydraulic structures and are the most used tools in drainage design for many engineering applications in the country (Zimale and Beyene, 2017). ERA (2013) classified the country in eight regions where rainfall is assumed homogenous (Fig. 2), aggregating them in four macro areas for which Zimale and Beyene (2017) provided empirical equations, in the form of Intensity-Duration-Frequency – IDF curves, reported as in the following:

$$I = \frac{389.06 \quad Tr^{0.22}}{t_p^{\quad 0.65}} \quad , \quad Region \quad A1\&A4 \tag{1}$$

$$I = \frac{336.98 \quad Tr^{0.21}}{t_p^{\quad 0.65}} \quad , \quad Region \quad A2\&A3 \tag{2}$$

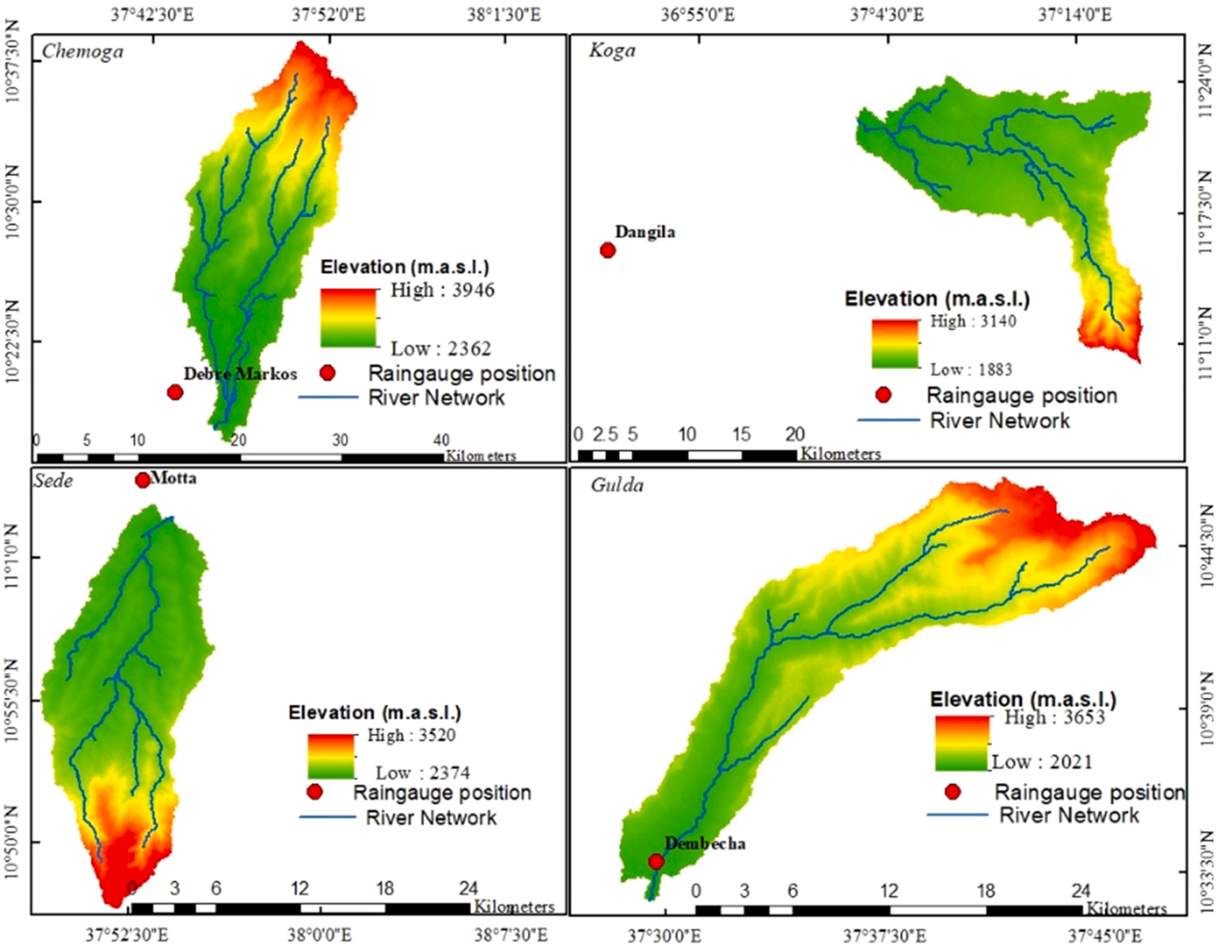


**Fig. 4.** Digital elevation models of the four case study watersheds: Chemoga, Koga, Gulda, and Sede.

$$I = \frac{421.47 \quad Tr^{0.21}}{t_p^{\ 0.65}} \quad , \quad Region \quad B1, \quad B2\&C \tag{3}$$

$$I = \frac{432.32 \quad Tr^{0.22}}{t_p^{\ 0.65}} \quad , \quad Region \quad D \tag{4}$$

where I is rainfall intensity (mm/h), Tr is the return period (y), and tp is the rainfall duration (min).

It is noteworthy that IDF and DDF curves are strictly related each other. Indeed, a DDF curve represents the analytical relationship, for a specified return period, between cumulative rainfall depth and rainfall duration, while an IDF curve represents the analytical relationship, for the same return period, between rainfall intensity and rainfall duration. Since rainfall intensity is defined as the ratio between cumulative rainfall depth and rainfall duration, multiplying the IDF curve for rainfall duration allows obtaining the DDF curve, and viceversa.

## 3. Materials

The case study area investigated in the present manuscript is included in the Upper Blue Nile river basin, which starts at Lake Tana and crosses the Ethiopia-Sudan border. The topographic feature of the Blue Nile river basin is highlands, hills, valleys, and occasional rock peaks (Alem et al., 2019). The average annual rainfall varies between 1100 mm and 1800 mm (Sutcliffe and Parks, 1999). Locally, the climatic seasons are defined as the dry season "Bega" from October to February; a short rain period "Belg" from March to May; and a long rainy period "Kiremt" from June to September, with the highest rainfall occurring in July and August (Alem et al., 2019).

Four small watersheds (Chemoga, Koga, Gulda, and Sede, see Fig. 3), characterized by contributing areas in the range 211–349 $km^2$ and which are part of the Upper Blue Nile river basin and are included in the Amhara regional state, have been selected for comparing the approaches described in the Section 4.

The elevation of the case-study watersheds was retrieved by using a 30 m resolution DEM acquired from the NASA Shuttle Radar

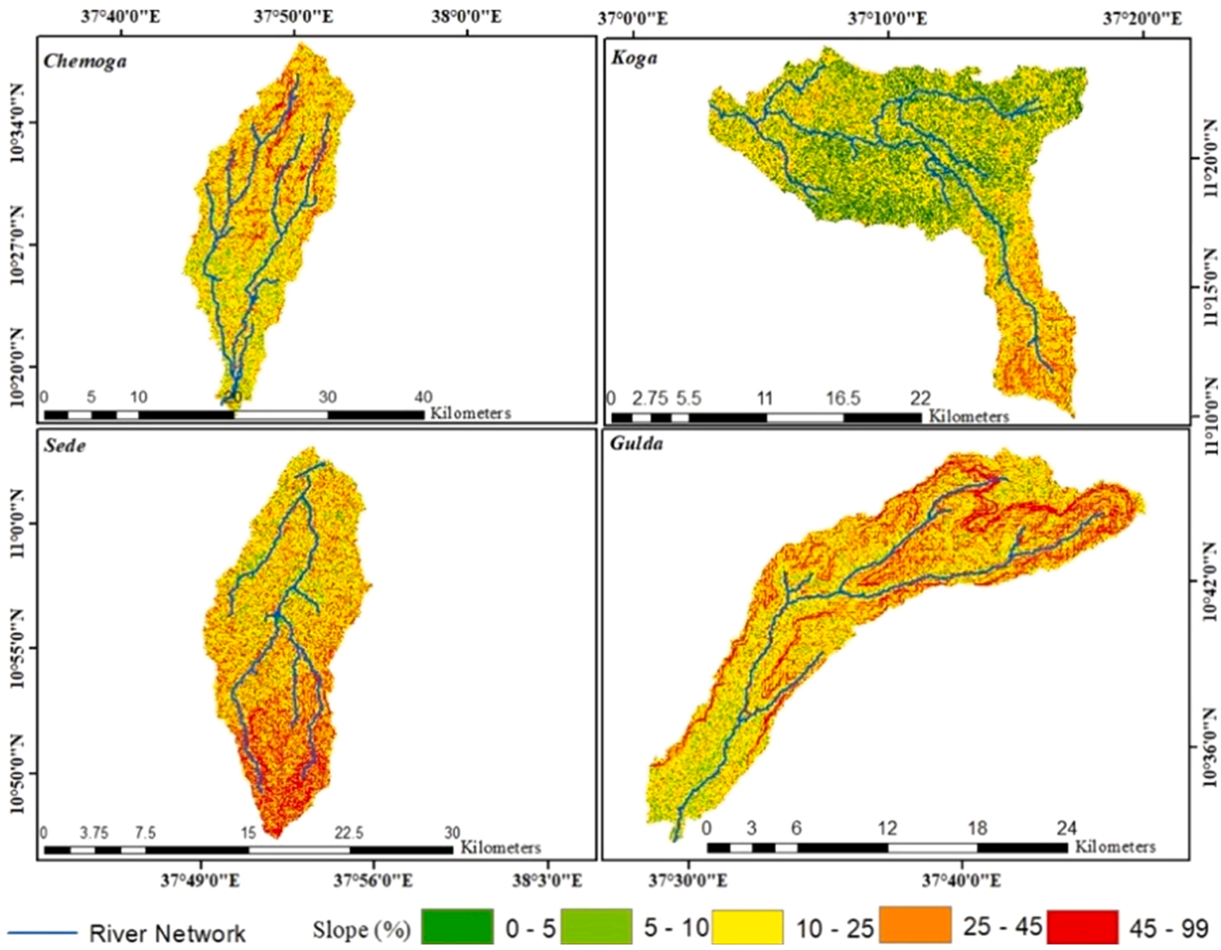


**Fig. 5.** Slope maps of the four case study watersheds.

Topographic Mission (SRTM) (Fig. 4). The elevation of Chemoga watershed ranges from 2362 to 3946 m above sea level (m.a.s.l), Koga from 1883 to 3140 m.a.s.l, Gulda from 2021 to 3653 m.a.s.l, and Sede from 2374 to 3520 m.a.s.l. Among the selected watersheds, Chemoga has the highest elevation. It originates from the Chockie Mountain, which is also called the "water tower" of the Upper Blue Nile Basin. Gulda and Sede watersheds are also originated from the Chockie Mountain and have high elevations, while Koga watershed, which is located in a flat area in the Lake Tana basin, has comparatively lower elevations.

The analyzed watersheds have different slope (Fig. 5), ranging from 0 % to above 45 %. The dominant slope of the investigated watersheds is between 10 % and 25 %. It accounts for 47.97 %, 44.29 %, 42.34 %, and 43.13 % of Chemoga, Koga, Gulda, and Sede watersheds, respectively. Sede and Koga have larger areas with slope lower than 10 % (17.34 %, and 14.35 %, respectively), while Gulda has larger areas covered by slope greater than 45 %.

The land cover of the investigated watersheds, referred to 2016 and collected from Amhara Design and Supervision Works enterprise office, is shown in Fig. 6. The Upper Nile Basin dominant land use is agricultural land and it covers a large portion of all the investigated watersheds (75.9 %, 90.7 %, 87.2 %, and 75.6 % for Chemoga, Koga, and Gulda, and Sede watersheds, respectively). Chemoga and Sede have larger grassland areas (12.2 % and 11.7 %, respectively) than the other studied watersheds. Gulda, Sede, and Chemoga watersheds have also high tree cover areas (13.5 %, 12.4 %, and 10.5 %, respectively).

From Fig. 7, the dominant soil types in the Chemoga watershed are Pellic Vertisols and Chromic Luvisols which cover about 47 % and 35 %, respectively, of the total area. Chromic Luvisols and Eutric Nitisols cover the largest area (about 56 % and 29 % of the total area, respectively) of the Gulda watershed. Dystric Gleysols cover the largest area (48 % of the total area) in the Koga watershed and are followed by chromic Vertisols, which cover about 25 % of the total area. Finally, regarding Sede watershed, Pellic Vertisols cover the largest area, about 74 % of the total area, followed by Chromic luvisols, that cover 12 % of the total area.

Each watershed was associated with the nearest meteorological stations (Chemoga to Debre Markos station, Koga to Dangila station, Sede to Motta station, and Gulda to Dembecha station, see Fig. 4). The four rainfall stations provide daily rainfall data from 1985 to 2020 and are C3 stations following the NMA classification. There are also streamflow gauge stations in each outlet, but they were only recently installed and so they are unable to provide useful flow data for the present analysis.

The mean annual rainfall estimated at Dangila, Dembecha, Debre Markos, and Motta meteorological stations was 1569 mm,

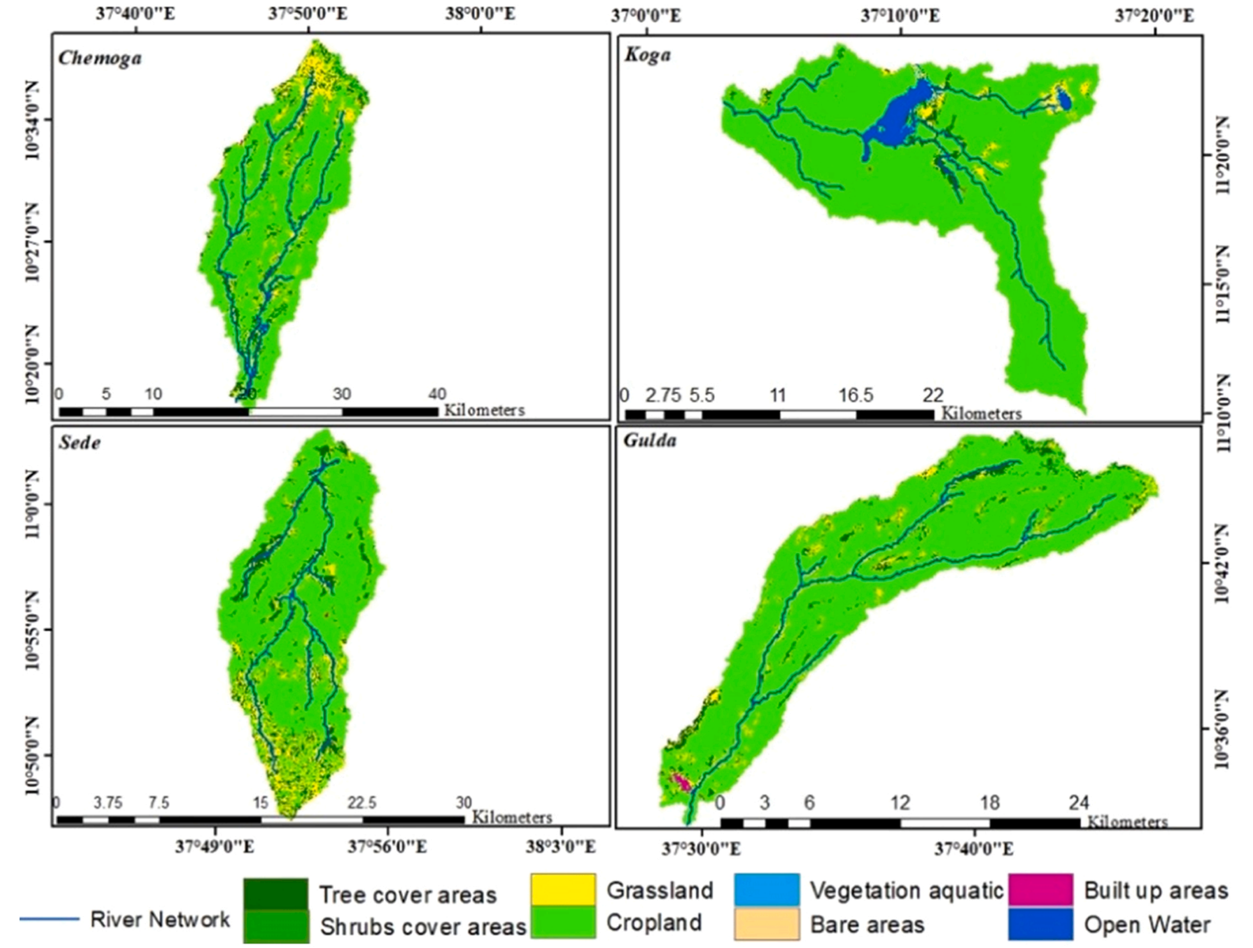


**Fig. 6.** Land use maps of the four case study watersheds.

1385 mm, 1341 mm, and 1226 mm, respectively. The highest rainfall is recorded at Dangila meteorological station while the lowest rainfall is recorded at Motta meteorological station. The mean monthly rainfall shows the highest record in July at Dembecha and Motta stations and in August at Dangila and Debre Markos stations. December, January, and February have low rainfall records based on the information obtained from all the stations.

Since the four watersheds are included in same rainfall region (A2), the DDF curves, derived by Eq. (2), are represented by the following Eq. (5):

$$h_p = 23.54 \quad T_r^{0.21} \quad t_p^{0.35} = a \bullet t_p^{n} \tag{5}$$

with $a = 23.54T_r^{0.21}$ and $n = 0.35$ and where: $h_p$ is the cumulative rainfall depth (mm), $t_p$ the rainfall duration (h), $n$ (–) and $a$ (mm/h$^n$) the DDF parameters based on the assumed return period $Tr$ (y).

In the following Table 2 we report a summary description of the used data input.

## 4. Methods

### 4.1. The rational formula

The rational formula (Mulvaney, 1851) is probably the most known and used worldwide method to estimate the design discharge for a catchment (Eq. (6)):

$$Q_P = C_t \frac{h_p}{T_C} A \tag{6}$$

where: $Q_P$ is the peak discharge (m$^3$/s); $C_t$ is runoff coefficient (–); $h_p$ is the cumulative rainfall depth (m); $T_c$ is the basin concentration time (s), here estimated by the Giandotti (1934) formula; $A$ is the watershed area (m$^2$).

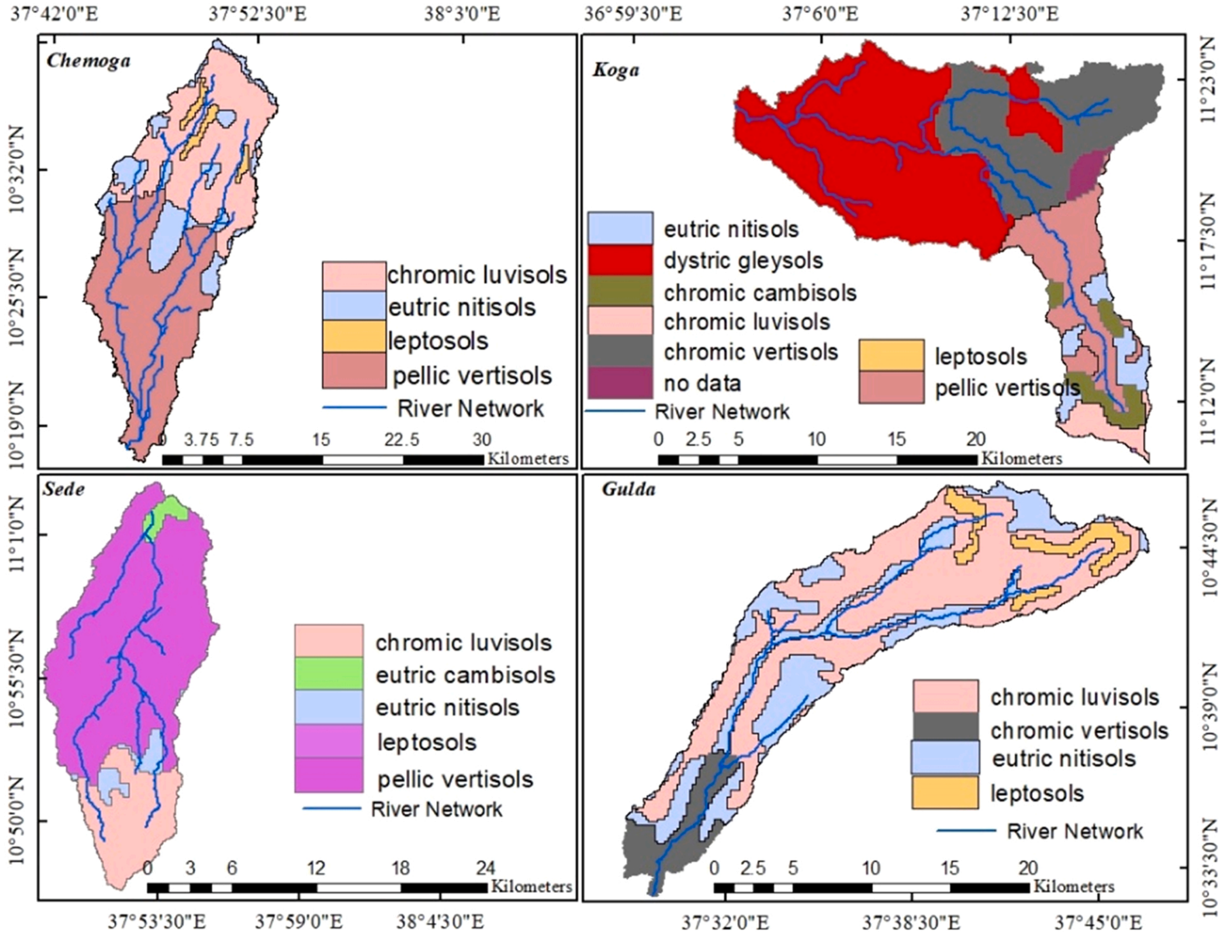


**Fig. 7.** Soil type maps of the four case study watersheds.

**Table 2**
Summary of used data input.

| Material | Source | Notes |
|---|---|---|
| Rainfall data – daily | National Meteorology Agency (NMA) | years from 1985 to 2020 |
| Rainfall data – DDF curves | Ethiopian Road Authority (ERA) | equations provided in 2017 |
| DEM | NASA Shuttle Radar Topographic Mission (SRTM) | 30 m spatial resolution |
| Land Cover | Amhara Design and Supervision Works enterprise office | vector, year 2016 |
| Soil type | Amhara Water Irrigation and Energy bureau | raster, year 2015 |

Although the method is diffuse, its drawbacks are well recognized and documented in literature (Grimaldi and Petroselli, 2014).

The Hydraulics Manual, used by the Ethiopian Road Authority for the drainage design (ERA, 2013) suggests to include one adjustment coefficient in the Eq. (6) for better reproducing the infiltration processes in case of high intensity storms and for better characterizing the slope, land use and land type in the runoff coefficient. Consequently, the formulation adopted in this study is expressed by Eq. (7):

$$Q_P = C_f C_t \frac{h_p}{T_C} A \tag{7}$$

where: $h_p$ is the cumulative rainfall depth (m) quantified through the DDF curve (Eq. (5)); $T_c$ is the concentration time (s); $C_f$ is a frequency factor (–), function of return period; $C_t = C_S + C_P + C_v$ is the adjusted runoff coefficient (–) where $C_S$ is based on slope, $C_P$ is based on soil permeability, and $C_P$ is based on land-use type. Such coefficients are estimated using the equation available in the Ethiopian Road Authority Manual table 5.9 (ERA, 2013) and using the information shown in Fig. 5 (slope), Fig. 6 (land use) and Fig. 7 (soil type).

### 4.2. EBA4SUB – the event-based rainfall-runoff modeling

EBA4SUB (Event-Based Approach for Small and Ungauged Basins) model is an empirical-conceptual rainfall-runoff model that has been developed in recent years (Piscopia et al., 2015) for estimating the design hydrograph. It consists of three steps: design hyetograph estimation, excess rainfall estimation, and excess rainfall-runoff transformation.

In the first step, the DDF function is used for quantifying the cumulative rainfall depth ($h_p$) for different return periods $T_r$ assuming as critical rainfall duration the catchment concentration time ($T_c$). Then, the Chicago hyetograph is selected for determining the design rainfall temporal distribution (Petroselli et al., 2020a, 2020b). As in the rational formula, the Giandotti formula for estimating the concentration time and the Eq. (5) representing the DDF function are used also in EBA4SUB application.

In the second step, the excess rainfall is estimated using the CN4GA (Curve Number for Green-Ampt) procedure (Grimaldi et al., 2013b). CN4GA is a mixed and automatic approach that combines the Curve Number (CN) method (Natural Resources Conservation Service (NRCS), 2008) and the Green-Ampt physically based infiltration equation (Green and Ampt, 1911) to estimate the excess rainfall temporal distribution starting from design rainfall. In the present analysis, we compared the three Antecedent Moisture Condition (AMC) classes: I (dry soil), II (soil in average wetness conditions), and III (wet soil). The only parameter to be assessed in this step is the CN, ranging from 0 (no runoff, the whole rainfall amount becomes infiltration) to 100 (no infiltration, the whole rainfall amount becomes runoff), that is quantified based on land use (Fig. 6) and soil type (Fig. 7) (Natural Resources Conservation Service (NRCS), 2008) employing the original look-up tables.

In the third and last step, the excess rainfall–runoff transformation is estimated applying the WFIUH (Width Function-Based Instantaneous Unit Hydrograph), based on basin travel time distribution that is automatically calculated from DEM flow paths and $T_c$ value. In detail, surface flow velocities are calculated based on local slopes and land cover employing empirical formulas for hillslope cells and calibrating river network cells ensuring that the projection of the WFIUH center of mass on the temporal axis is equal to the basin lag time, that is expressed as 60 % of $T_c$ (Natural Resources Conservation Service (NRCS), 2008; Petroselli and Grimaldi, 2018).

In summary, EBA4SUB needs the same input data as the rational formula. The EBA4SUB peculiarity is to provide the entire design hydrograph using a procedure that reduces the subjectivity and the sensitivity of the rational formula (Grimaldi and Petroselli, 2014).

### 4.3. STORAGE – the synthetic rainfall timeseries

As described in the introduction, a continuous rainfall-runoff modeling needs as input a long synthetic rainfall scenario, that is transformed in the corresponding runoff scenario. In the present work, we used the recently released STORAGE (STOchastic RAinfall GEnerator) model (De Luca et al., 2020; De Luca and Petroselli, 2021; Grimaldi et al., 2022) to create the long synthetic rainfall timeseries. STORAGE is a Synthetic Rainfall Generator (SRG) model, able to reconstruct a long (up to 500 years) and high-resolution (up to 5 min) rainfall timeseries based on limited raingauge observations. STORAGE is a modified version of the Neyman–Scott Rectangular Pulses (NSRP) stochastic rainfall model (Burton et al., 2010). In STORAGE, five parameters play a crucial role and they are represented by the mean values for the following random variables:

- the waiting time (assumed as exponentially distributed) between the occurrences of two consecutive storms;
- the number of rain cells (also named as bursts or pulses) in each storm. This quantity is considered as a geometric random variable;
- the waiting time (assumed as exponentially distributed) between the occurrences of a storm and of an associated cell;
- the intensity and the duration (both considered as exponentially distributed) of each cell inside a storm.

STORAGE introduces two main innovations as respect to the basic NSRP models. First, the parametric estimation is carried out by using aggregated data (annual maxima rainfall, annual and monthly cumulative rainfall, annual number of wet days) which are usually more available compared to the high-resolution rainfall information (which are commonly considered for calibration of the basic NSRP models). Second, the seasonality is modeled using series of goniometric functions (sine and cosine). This approach makes STORAGE strongly parsimonious as respect to the use of monthly or seasonal sets for parameters, as it usually occurs for basic versions of NSRP models. Such characteristics allow STORAGE to be particularly promising for reconstruction of rainfall fields in data scarce areas (Petroselli et al., 2021).

It must be highlighted that the proposed case study analysis is implemented under the hypothesis of stationary processes. In fact, authors retained that trend analysis for observed time series could be not reliable when case studies with scarce data (like in this work) are investigated.

### 4.4. COSMO4SUB – the continuous rainfall-runoff framework

The continuous rainfall-runoff modeling is here carried out by using COSMO4SUB model with STORAGE results as rainfall input. COSMO4SUB (Continuous Simulation Model For Small and Ungauged Basin) (Grimaldi et al., 2012a, 2021, 2022) is the continuous version of EBA4SUB model and 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.

Regarding the first step, for the proposed application, the rainfall timeseries is represented by 500 years at 15 min resolution generated by STORAGE model in stationary conditions. In particular, each case study is associated with a reference raingauge and the observed rainfall data are used for simulating the corresponding rainfall timeseries.

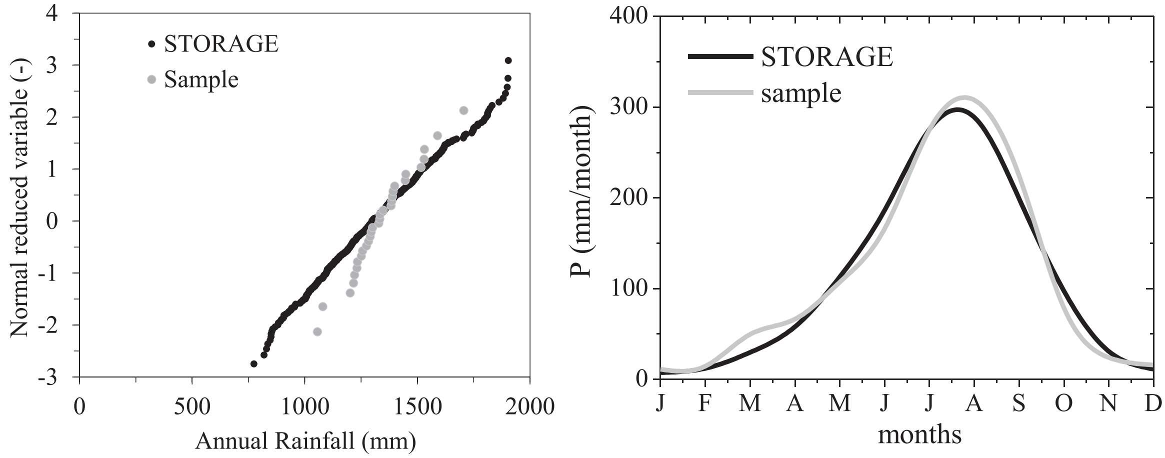


**Fig. 8.** Debre Markos raingauge: yearly (left) and monthly (right) cumulative rainfall values.

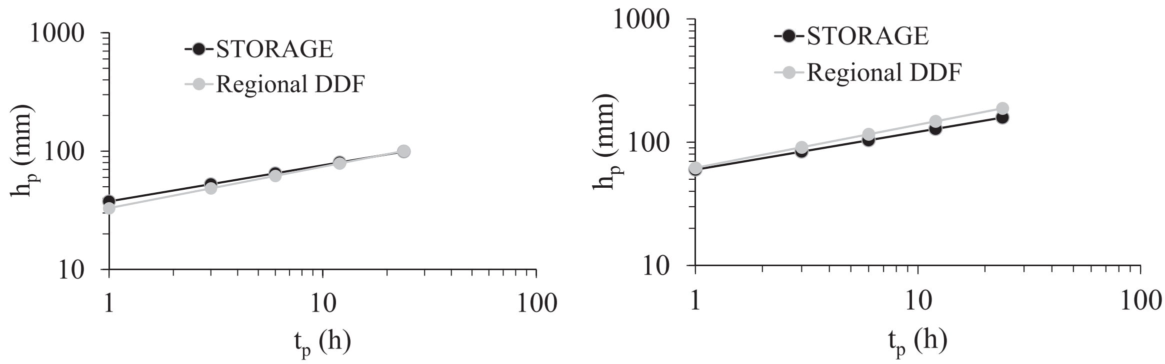


**Fig. 9.** Debre Markos raingauge: 5-year (left) and 100-year (right) DDF curves.

Regarding the second step, a continuous version of CN4GA is implemented. It needs an additional parameter compared to the event-based version, named separation time (*Ts*), that represents the dry period that should be waited in order to consider independent the rainfall events so that the initial abstraction become again effective. Previous works suggest 24 h for *Ts* value (Grimaldi et al., 2012a, 2021). So, model parameters inherent to this step are essentially CN (in AMC-II condition) and *Ts*. The continuous version of CN4GA procedure is able to automatically assess the AMC condition based on the amount of rainfall occurred in the five antecedent days and to accordingly modify the CN-II value (Natural Resources Conservation Service (NRCS), 2008).

Regarding the third step, the same version of the WFIUH used in the EBA4SUB model was used. The application of the first three steps of COSMO4SUB allows obtaining a 500-year runoff timeseries, from which the design simulation strategy (step 4 of the model) can be assessed. Here, we selected the annual maxima of peak discharge and its related hydrograph, moreover we determined the peak discharge – return period relationship based on the empirical distribution according the following equation:

$$\frac{j}{n+1} = 1 - \frac{1}{T_r} \tag{8}$$

where $j = 1,\ldots,n$ represents the *jth* observation of the samples arranged in ascending order an *Tr* (y) the return period.

### 4.5. The comparison analysis

In order to evaluate if COSMO4SUB model is appropriate in Ethiopian watersheds, ideally we should compare the simulated results with observed data or similar information (Grimaldi et al., 2012a, 2012b). However, when such benchmark is not available, the only possible solution is to compare the results with the typically adopted approaches and to evaluate the differences. Consequently, the described models are applied on the investigated case studies and evaluated comparing the design peak discharge related to the following *Tr* values: 2, 5, 10, 20, 50, 100, and 200 years. The comparison is based on different model configurations: a) rational formula; b) EBA4SUB (for AMC I, II and III) employing the regional DDF parameters; c) STORAGE + COSMO4SUB continuous modeling approach. Each model is calibration free and uses the same input information: DDF functions (Eq. (5)), DEM, slopes, land use and soil type (Figs. 4–7) except STORAGE (adopted as input for COSMO4SUB) that is calibrated using:

**Table 3**
Case studies area, concentration time and CN values.

| Case-study watershed | Raingauge station | Area (km$^2$) | Tc (h) | CN (–) AMC-I | CN (–) AMC-II | CN (–) AMC-III |
|---|---|---|---|---|---|---|
| Chemoga | Debre Markos | 349.8 | 8.9 | 55.9 | 75.1 | 87.4 |
| Gulda | Dembecha | 246.5 | 7.4 | 53.3 | 73.1 | 86.2 |
| Koga | Dangila | 299.1 | 11.8 | 59.2 | 77.6 | 88.8 |
| Sede | Motta | 211.0 | 9.1 | 60.0 | 78.1 | 89.1 |

**Table 4**
Final runoff coefficient values for rational formula application, i.e.$C_f C_t$ in Eq. (7).

| Case-study watershed | Tr (years) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 | 5 | 10 | 20 | 50 | 100 | 200 |
| Chemoga | 0.483 | 0.483 | 0.483 | 0.531 | 0.580 | 0.604 | 0.628 |
| Gulda | 0.479 | 0.479 | 0.479 | 0.527 | 0.575 | 0.599 | 0.623 |
| Koga | 0.539 | 0.539 | 0.539 | 0.593 | 0.647 | 0.674 | 0.701 |
| Sede | 0.519 | 0.519 | 0.519 | 0.571 | 0.623 | 0.649 | 0.675 |

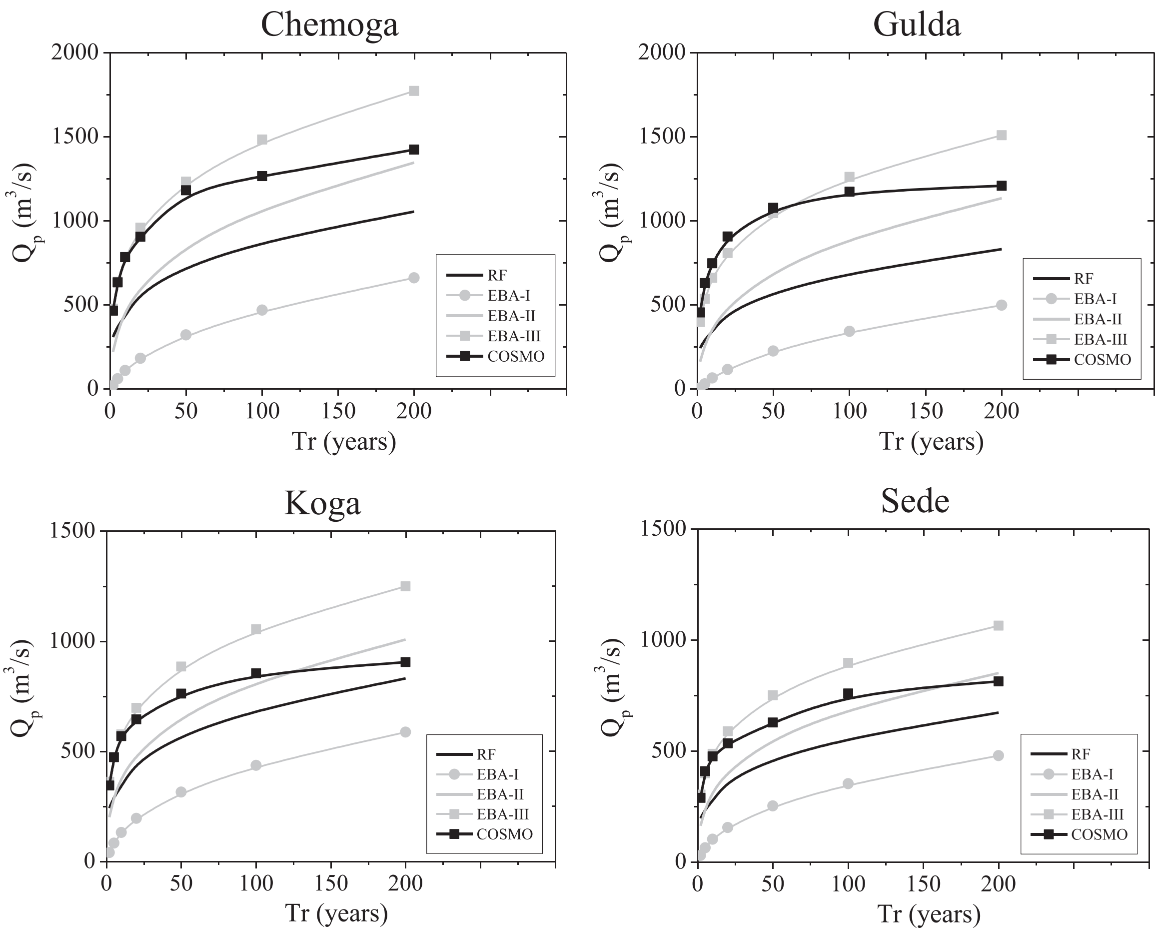


**Fig. 10.** Relationship between return period (*Tr*) and peak discharge ($Q_p$). RF: rational formula. EBA-I, EBA-II, EBA-III: EBA4SUB application for AMC-I, AMC-II, AMC-III. COSMO: COSMO4SUB application.

1. the specific observed data for each raingauge, extracted from the continuous daily time series, i.e.: daily Annual Maxima (AM) series, Mean Annual Precipitation (MAP), mean values of seasonal precipitation (December-January-February; March-April-May; June-July-August; September-October-November), Mean Annual Number of Wet Days (MANWD);
2. DDF curves, provided by the Ethiopian Road Authority, with regional values of "*a*" and "*n*" quantified using Eq. (5).

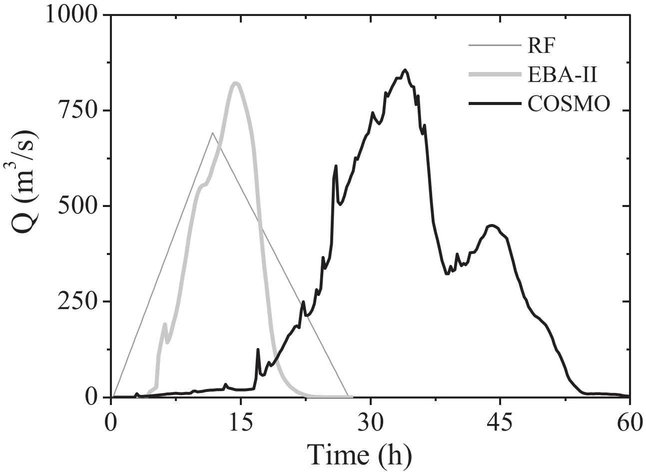


**Fig. 11.** Koga design hydrographs, $Tr = 100$ years. RF: Rational method (triangular method; Natural Resources Conservation Service (NRCS), 1986). EBA-II: EBA4SUB in AMC-II. COSMO: COSMO4SUB.

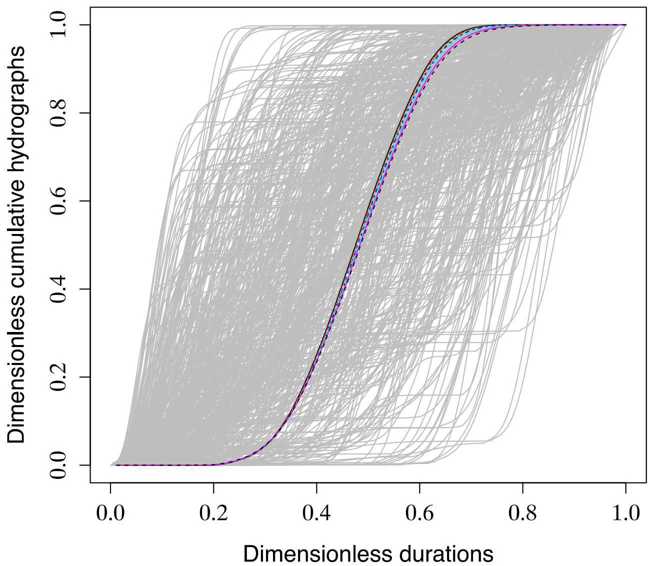


**Fig. 12.** Dimensionless cumulative synthetic hydrographs resulting from COSMO4SUB model (500 grey lines) and from EBA4SUB model (AMC-II, 7 colored lines, each one for a specific *Tr*). Hydrographs are normalized dividing the base by its duration and multiplying each ordinate by the ratio duration/volume (see Grimaldi et al., 2012a, 2012b).

Ideally, STORAGE should have been calibrated referring only to the raingauge observations, however we preferred to use a mixed information source (point 1 and 2). This is either because the amount of observed data at high time resolution are limited and also because the regionalized DDF curves are the official reference for Ethiopian practitioners.

## 5. Results and discussion

Concerning STORAGE calibration, Figs. 8 and 9 show the obtained results for Debre Markos raingauge. For sake of brevity, results for the other stations are shown in Appendix A. The outcomes, for all the investigated raingauges, highlight a satisfying reproduction for: annual rainfall values, monthly seasonal component, and DDF curves. Results depicted in Figs. 8 and 9, and in Appendix A, show that STORAGE model can effectively be employed for modeling rainfall in Ethiopia region, also if few rainfall data are available.

Focusing on the application of the rational formula, the EBA4SUB model for the three AMC classes and the COSMO4SUB model on the four case studies, the results are summarized in Tables 3 and 4 and Figs. 10–12.

In detail, Table 3 includes the contributing areas, CN and *Tc* values used in the three compared models while Table 4 shows the runoff coefficient adopted in the rational formula application, i.e. the product of $C_f C_t$ in Eq. (7).

Fig. 10 shows the comparison among the hydrograph peak values estimated for the seven return periods. Gray lines refer to the three AMC classes included in the EBA4SUB framework and, in practice, they offer a complete overview of all possible results, since the CN values span in a very wide range. Peak discharges resulting from the rational formula are always lower than the corresponding obtained with EBA4SUB in AMC-II condition. This expected behavior is due to the runoff coefficient: indeed, although it is adjusted, it underestimates the excess rainfall for extreme storms, due to the proportional relationship between gross rainfall and runoff.

Concerning the peak discharge values obtained with COSMO4SUB application, they are included in the range of EBA4SUB AMC-II and AMC-III. This is also expected since in the continuous modeling scheme the AMC is variable and related to the rainfall amount collected in the five days before the storms. This is one of the benefits of the continuous approach that allows to overcome the limitation of the event-based and rational formula methods, offering a more realistic representation of rainfall input.

The obtained results are coherent with the previous related literature. For instance, Petroselli et al. (2019) determined with COSMO4SUB design peak discharges (that were lower than the corresponding ones obtained with EBA4SUB in AMC-III condition but higher than the corresponding ones obtained with EBA4SUB in AMC-II condition) and highlighted the critical role of AMC and how subjective the event-based approach is for the design hydrograph estimation. Moreover, Grimaldi et al. (2012b) compared the continuous modeling with event-based approaches applied with AMC II. They concluded that estimations from the continuous modeling are generally greater than the corresponding ones from event-based approaches, with differences, for 100-year return period, in the range 20–40 %. Finally, Winter et al. (2019) highlighted that peak discharge values obtained with a continuous modeling were systematically higher than event-based ones. In this last contribution, the authors argued that the event-based approaches could not fully account for the variability of possible flood events, and that their use may lead to an underestimation of peak discharge in comparison to a continuous modeling. This circumstance is particularly important in applications like flood mapping, where the potential damages are influenced by both flood peak and runoff volume.

Another added value provided by COSMO4SUB model is related to the hydrograph attributes. Indeed, while the rational formula provides only the peak discharge, the event-based and continuous approaches estimate also the flood hydrograph shape and the related characteristics such as total volume and duration. It is true that, after having estimated the design peak discharge with the rational formula, it could be possible to employ synthetic equations (e.g. Natural Resources Conservation Service (NRCS), 1986) in order to determine the design hydrograph ascending and descending limb, but this procedure does not keep in account the basin geomorphic properties, providing not realistic flood volume and duration. For instance, in Fig. 11, the design hydrographs, for $Tr = 100$ years, obtained with the rational formula and the triangular method (Natural Resources Conservation Service (NRCS), 1986) for determining the hydrograph shape, plus with EBA4SUB (AMC-II) are shown for Koga case study. Fig. 11 shows also one of the COSMO4SUB annual maxima hydrographs having a peak discharge similar to the design peak discharge that is shown in Fig. 10. Looking at Fig. 11, differences in the hydrograph shape (affecting flood duration and total volume) are evident. The rational method provides a hydrograph with a potentially unrealistic duration and volume. In EBA4SUB it is evident the irregular shape of the design hydrograph, due to the WFIUH geomorphological signature of the watershed, circumstance that highlights the benefit offered by EBA4SUB as respect to the use of the rational formula. A more realistic shape is offered by COSMO4SUB due to the simulated storms. Indeed, the continuous runoff time series allows to select the extreme floods that are not constrained to the critical rainfall definition as in the EBA4SUB model. In order to provide a further visual evidence of this, Fig. 12 shows all the maximum annual hydrographs (in terms of peak discharge) generated by COSMO4SUB, plus the seven design hydrographs generated by EBA4SUB (AMC-II).

This simple comparison allows to verify that the COSMO4SUB results are coherent to the EBA4SUB and rational formula outputs. Indeed, we expected that the rational formula underestimates the peak discharge for high return period compared to the EBA4SUB model (AMC-II), and that the COSMO4SUB peak discharges are within the range of EBA4SUB outputs obtained with AMC-II and AMC-III, due to the automatic AMC quantification from the input synthetic rainfall time series.

## 6. Conclusions

The present work aims at verifying the potentiality in Ethiopia to adopt more advanced procedures for estimating design hydrographs in small basins, as respect to the use of the rational formula that is commonly used in the country. Indeed, the review of the currently available hydrological information confirmed a limited amount of observed rainfall data and the absence of discharge observations, circumstance that would justify the use of the rational formula.

Hence, a comparison among three rainfall-runoff models has been performed for four case studies. Specifically, the widely used rational formula, an event-based approach (EBA4SUB model) and a continuous framework specifically tailored for small and ungauged basins (COSMO4SUB model) have been applied on Chemoga, Koga, Gulda, and Sede catchments, located in the Upper Blue Nile Basin for estimating the design hydrographs related to various return periods spanning in the range 2–200 years. The comparison allows for verifying the behavior of advanced models as respect to the rational formula. Results are in line each other reproducing expected differences: the underestimation of peak discharges resulting from rational formula, and more realistic peak discharge values offered by COSMO4SUB that can optimize the available rainfall information for identifying the soil moisture condition before the storm. Moreover, the added values of the continuous framework is emphasized showing the variety of available hydrographs characterized by realistic shapes.

The obtained results support the conclusion that Ethiopia has enough hydrological information for implementing simplified continuous modeling in the country. However, we realize that an effort could be made for improving the rainfall observations providing a more homogeneous raingauge network useful for updating the regional DDF curves parameters. Moreover, the quality of the instrumentation for assuring sub-daily monitoring crucial for rainfall simulation models could be enhanced as well.

## 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.

## Acknowledgements

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## Appendix A

See Figs. A1–A6.

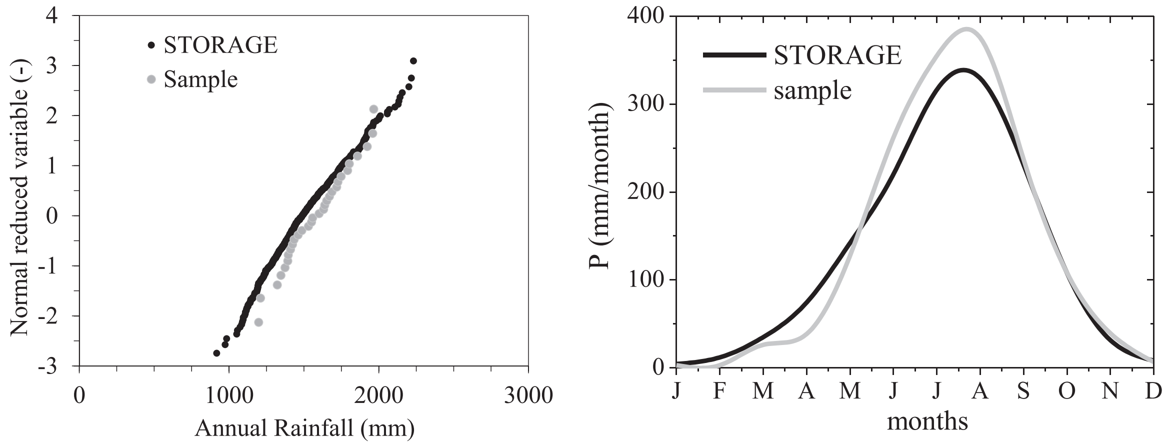


**Fig. A1.** Dangila raingauge: yearly (left) and monthly (right) cumulative rainfall values.

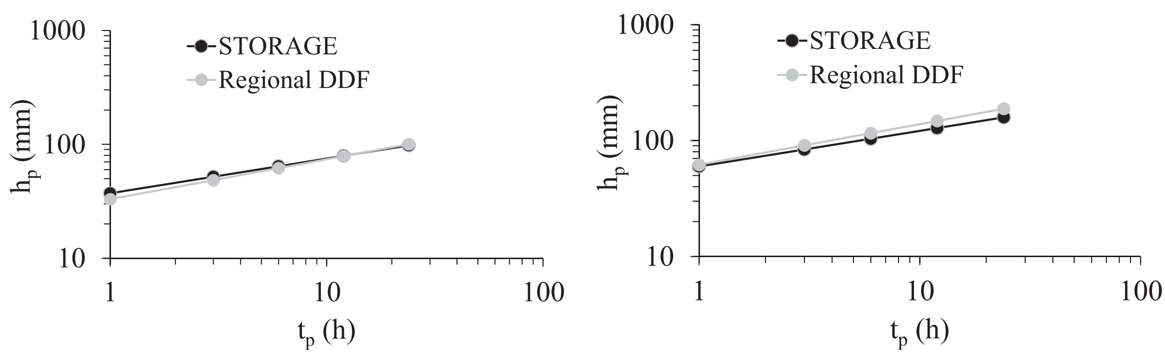


**Fig. A2.** Dangila raingauge: 5-year (left) and 100-year (right) DDF curves.

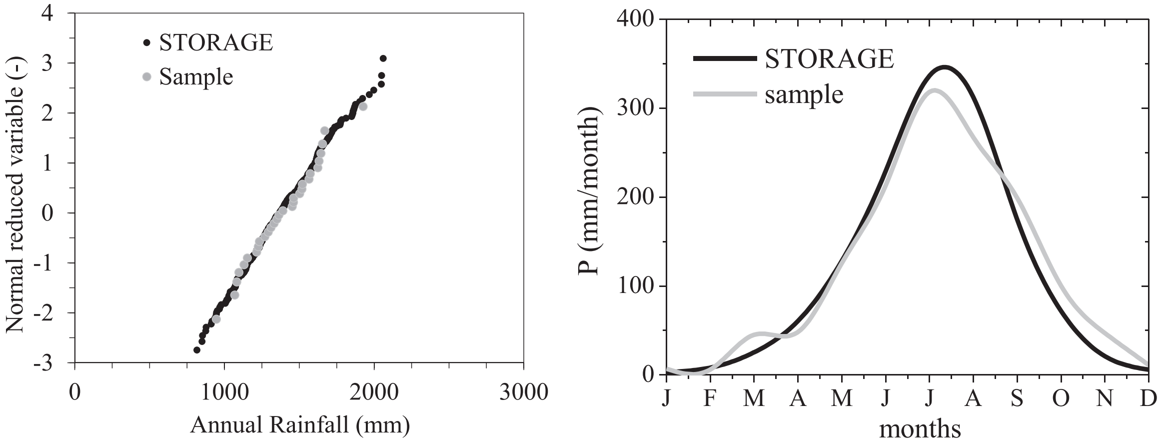


**Fig. A3.** Dembecha raingauge: yearly (left) and monthly (right) cumulative rainfall values.

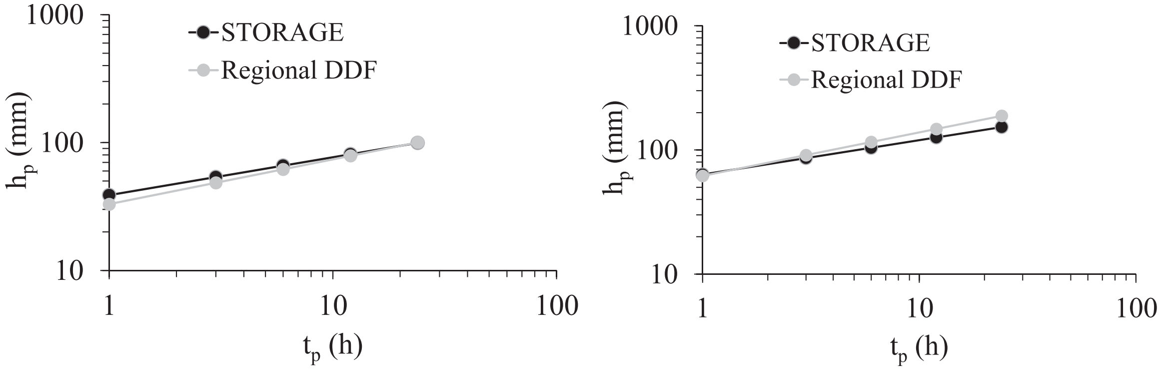


**Fig. A4.** Dembecha raingauge: 5-year (left) and 100-year (right) DDF curves.

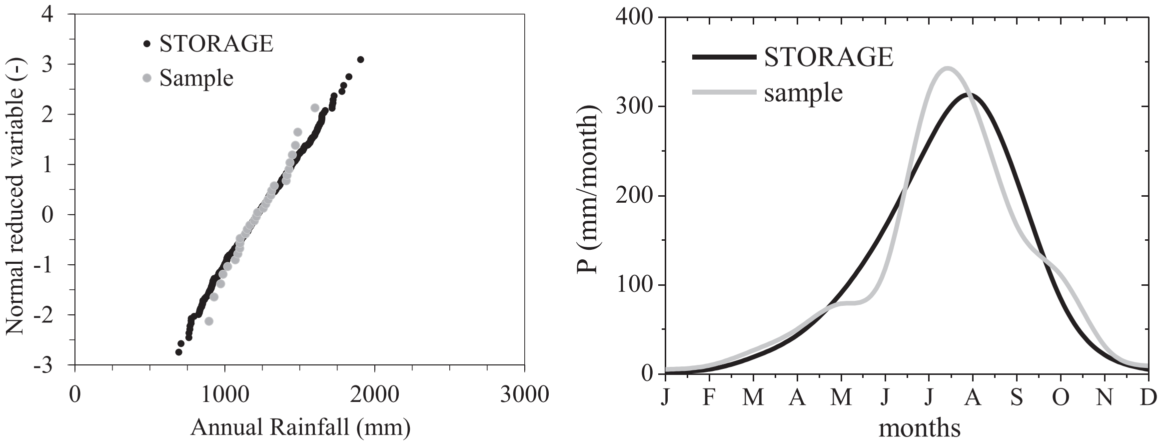


**Fig. A5.** Motta raingauge: yearly (left) and monthly (right) cumulative rainfall values.

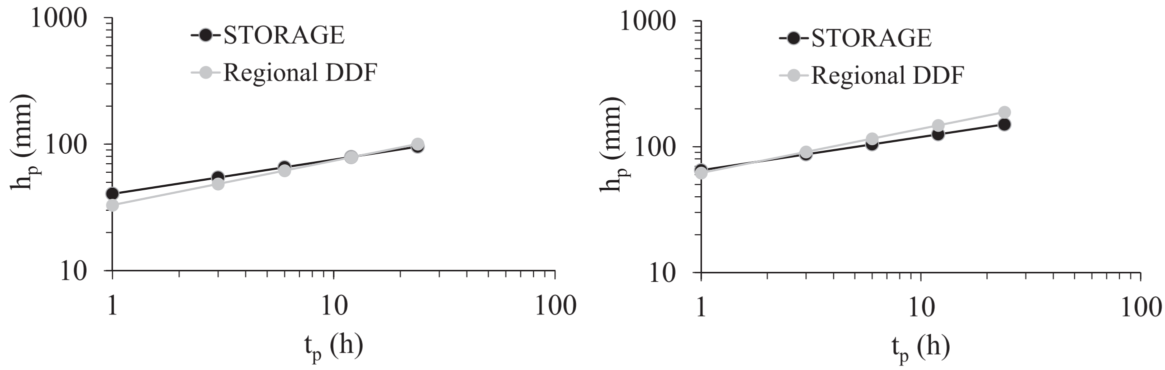


**Fig. A6.** Motta raingauge: 5-year (left) and 100-year (right) DDF curves.

## Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101123.

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