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Estimating the runoff response from hillslopes treated with soil and water conservation structures in the semi-arid Ethiopian highlands: Is the curve number method applicable?

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A B S T R A C T

Planning and management of water resources is crucial to enhance agricultural productivity and ensure food security in drylands. For this, adaptable and reliable runoff prediction models are urgently needed to support water harvesting and irrigation development. In this study we explored the potential of the runoff Curve Number (CN) method to estimate daily surface runoff from representative land use types and management conditions in Tigray (north Ethiopia). For this, we use the National Engineering Handbook (NEH-Tables) to derive CN values for runoff plots treated with and without soil and water conservation (SWC) structures. Moreover, the rainfall-runoff data collected from 21 large (600–1000 m^2) runoff plots during three years (2010 to 2012) were used to calculate CN-values. Results show that CN values derived from the NEH-Tables are larger by 21% compared to those values calculated from plot data. The calculated CN values vary widely (34 to 91) in response to land use type, slope gradient, and applied SWC structures. Our results show that land use and SWC structures strongly influence runoff production. Considering plots with otherwise similar characteristics, CN values are consistently larger for rangeland sites as compared to those values for cropland sites. Likewise, SWC structures greatly reduce runoff production and their presence also leads to a clearly lower performance of the CN model. The results of this study are relevant contributions towards addressing several goals of agenda 2063 of the African union either directly or indirectly and also international sustainable development goals (SDG). Based on our analysis and field observations, we propose calibrated CN values that may be used for runoff yield assessments in similar environments.

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Introduction

More than 67% of the Ethiopian landmass is drylands where rainfall is strongly seasonal and insufficient to support rain-fed agriculture [1,2]. These areas include arid, semi-arid and dry sub-humid agro-ecological zones representing diverse agricultural environments that support most of the human and livestock population of the country [3,4]. While the mean annual rainfall in the country is estimated at 1090 mm, more than 70% of the croplands receive less than 750 mm per year, mainly during a three months lasting rainy season [5–7]. Land degradation and recurrent drought combined with the impacts of climate change leads to vulnerability and to food insecurity [2,8,9]. Dry spells towards the end of the growing season can lead to a significant crop yield reduction or to a complete crop failure [10–13]. To mitigate these risks, water harvesting and irrigation development became a top priority in the drought-prone northern Ethiopian highland since the 1980's [6,14–16]. Large number of earthen micro-dam reservoirs and household ponds (*ca.* 150,000) were built for irrigation purposes [11].

Nonetheless the success of water harvesting systems in meeting desired targets of increasing area under irrigation and ensuring food security is limited particularly in Tigray. Haregeweyn et al. [17] indicated that reservoir siltation due to excessive hillslope erosion is the most important challenge for the sustainability of these runoff harvesting structures in Tigray. In response to the siltation of reservoirs, extensive soil and water conservation (SWC) measures and reforestation campaigns (using exclosures) were implemented in the catchments of these reservoirs. These measures are effective in reducing soil loss and reservoirs siltation [7,18–22]. However, they also lead to a drastic reduction of the runoff volume delivered to these reservoirs. This reduction is due to the increased runoff detention storages by the implemented SWC measures within the catchments [7,23,24]. Haregeweyn et al. [17] reported that 61% of the reservoirs constructed in Tigray before 2002 significantly suffered from insufficient inflow. This was attributed to different factors, including land management practices that were later implemented to control reservoir siltation. Remarkable inflow differences were observed before and after the implementation of these SWC measures. Based on the assessment made for 54 reservoirs constructed between 1994 and 2002, Haregeweyn et al. [17] indicated that almost all these reservoirs are operating at or below 50% of their original design capacity.

Effective water resource planning and management requires reliable estimate of key hydrological components such as runoff yield [25–27]. Yet, correctly parameterizing the models used for such estimates remains an important challenge. This is particularly true at a catchment scale, where heterogeneity in rainfall conditions and catchment characteristics make the hydrological processes more complex [28–32]. Overall, the planning and design of water resources in Ethiopia (and especially in Tigray) is being constrained by a lack of data such as rainfall-runoff, evaporation, land use types, soils, topography and geological characteristics of catchments and dam sites [14,17,33]. This lack of data leads to the application of lumped rainfall-runoff models that are not adapted to the local conditions and often remain unvalidated [16,17,27]. As a result, many reservoirs and related irrigation infrastructures are over-dimensioned.

Given its relative simplicity and its worldwide use, the most used model for such applications is the Curve Number (CN) method [30,34–36]. The CN method has been widely applied in arid and semi-arid areas for several purposes such as prediction of peak discharge and flood hazard [37–39], rainfall-runoff analysis for a proper planning and development of water resources in a watershed [40,41]. Reliable CN values for the different land-use-cover complexes that consider the potential effect of SWC structures is therefore crucial to optimize the design of water harvesting reservoirs in Tigray. However, for designing water harvesting reservoirs in Tigray, CN values obtained from the original National Engineering Handbook (NEH-Tables) are used [42]. These CN values were calculated from plot data in the USA for a temperate type of climate. Nonetheless, this region strongly differs from North Ethiopia in terms of land uses, topography, soil types, implemented SWC measures and climatic conditions (e.g. [5,7]). Only few studies confronted the CN method in Ethiopia with measured rainfall-runoff data. Descheemaeker et al. [43] applied the CN method for rangeland, exclosures and natural church forest using measured rainfall-runoff data at the runoff plot scale (2 m x 5 m). Teka et al. [16] also compared CN values calculated based on measured rainfall-runoff relations with those obtained from NEH-tables for ten sub-catchments in Tigray. Tessema et al. [27] used the CN method at large catchment scale as a component of the SWAT model to estimate surface runoff based on spatially varying storage index that depended on soil profile moisture content and potential evapotranspiration. Sultan et al. [44] tested the validity of the CN model parameters for five land use types and two slope ranges in a tropical humid watershed in the southwestern Ethiopia.

As such, the applicability of the CN method in Ethiopia remains poorly supported by measured data, especially in the more arid and semi-arid Tigray region. Furthermore, to the best of our knowledge, no study exists that accounted for the effects of SWC structures on CN values. Nonetheless, such SWC measures (e.g. stone bunds, soil trenches or a combination of both) are abundantly installed on sloping cropland and rangeland sites in Tigray. These SWC structures strongly reduced runoff production during one to two years after installation and their effectiveness in reducing runoff decrease over time because of sediment deposition and reduction of their storage capacity [45].

Here we aim to address this research gap. Building on rainfall-runoff data measured on large runoff plots over three rainy seasons [45], we attempt to calibrate and validate the SCS-CN method and investigate whether it can be applied to estimate surface runoff volume from hillslopes with SWC structures installed. More specific objectives are: (i) to derive and test CN values for rangeland and cropland runoff plots based on the soil-cover-complex using the original NEH-Tables; (ii) to calibrate and validate representative CN values for rangeland and cropland sites treated with and without SWC structures using measured rainfall-runoff data; (iii) to analyze the effect of temporal changes in the effectiveness of SWC structures

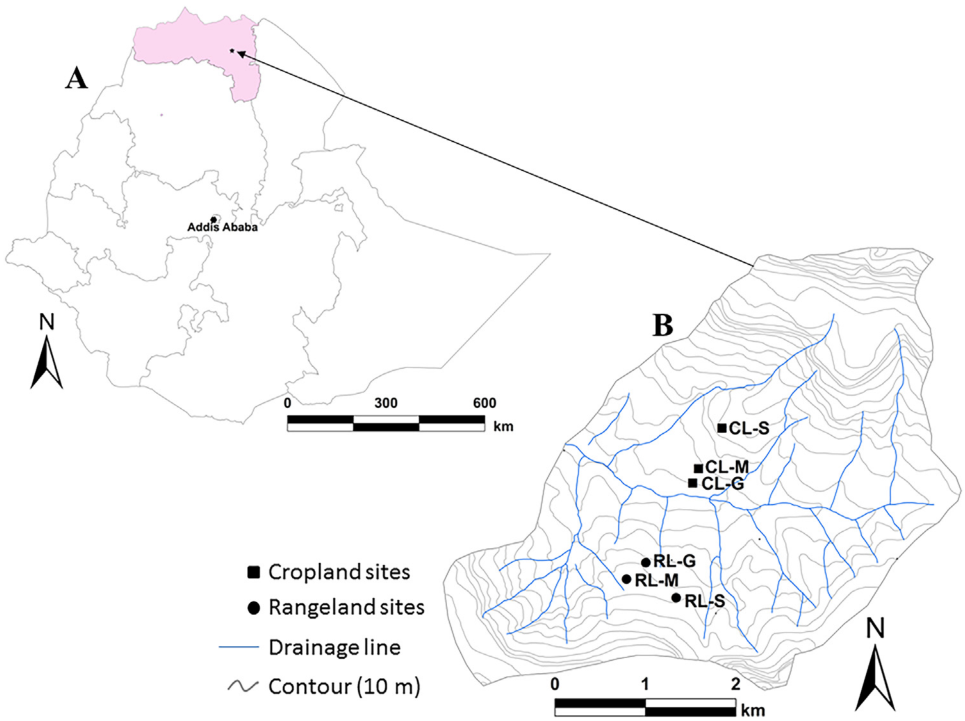

Fig. 1. Location of the study area: (A) in Ethiopia, (B) Mayleba catchment indicating the location of rainfall-runoff measuring sites for rangeland (RL) and cropland (CL) and at gentle (G), medium (M) and steep (S) slope gradients.

on the calculated CN values and; (iv) to evaluate the overall applicability of the CN method in semi-arid environments with SWC measures.

Materials and methods

Study area

The study was conducted in the Mayleba catchment (13°41′N, 39°15′E), Tigray, North Ethiopia (Fig. 1a). The catchment is located *ca.* 830 km north of Addis Ababa and *ca.* 40 km West of Mekelle (the regional capital). Its climate is a cool tropical semi-arid one with strong rainfall seasonality. The spatial-temporal variation in rainfall distribution is related to the Inter-Tropical Convergence Zone (ITCZ) [5,46]. More than 80% of the annual rainfall is concentrated during the main rainy season between June and September (Fig. 2; [5]). Rainfall outside the rainy season is highly variable and unreliable for a rain-fed agricultural production [12,22]. Annual potential evapotranspiration is estimated at 1639 mm, which is twice the value of the long-term mean annual rainfall depth *ca.* 700 mm [47]. Except for July and August, the monthly potential evapotranspiration exceeds the corresponding monthly rainfall. The length of the growing period is short and ranges from 45 to 120 days [48].

Topography of the north Ethiopian highlands is rugged with undulating hills, plateaus and mountain ranges [49]. There is a large altitudinal variation over a short distance inducing variations in rainfall depth, vegetation type, vegetation cover, soil erosion and runoff production [7,21]. Due to widespread deforestation and intense land degradation in response to early agricultural settlement and population growth [9,49], the rainfall-runoff response is rapid and leads to high rates of runoff, soil erosion and sediment export from agricultural watersheds [8,17,50,51]. This also holds for the Mayleba catchment. The lithology of the Mayleba catchment consists of alternating series of limestone and sandstones sequences (i.e. the Mekelle outlier; [22]). The Mekelle outlier is composed of Precambrian (metamorphic) basement overlain by alternating layers of Antalo Limestone and Agula Shales, Adigrat and Amba Aradam Sandstones of Mesozoic formation. The top part of this alternating layer is covered by two series of tertiary flood basalt locally separated by lacustrine deposit [52]. The layers are now exposed with interrupted original continuity owing to accelerated erosion and deep incision [53]. Due to this variability in parent material as well as the complex topographical setup, the catchment is characterized by different soil types. The major soil types are Leptosols, Vertic Calcisols, Vertic Cambisols, Regosols, Cambisols and Vertisols [54].

Dominant land use types within the catchment are croplands and rangelands. Some degraded rangelands on the hill-slopes are also converted to exclosures (protected area) for natural restoration of soils and vegetation [18,55,56]. Agriculture is mixed, involving crop and livestock production on the same farmlands. Croplands are tilled by traditional *ard* plough '*Ma-*

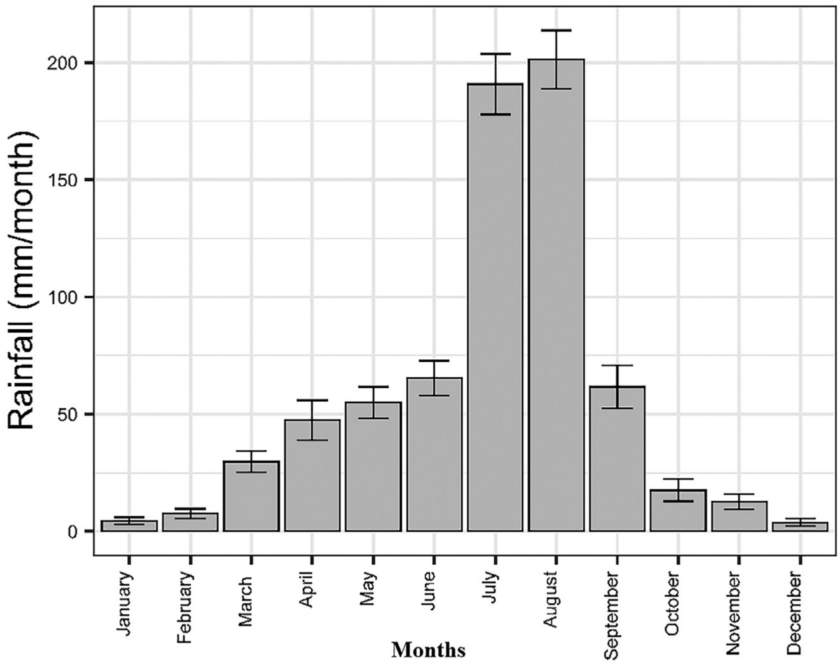

Fig. 2. Long-term (1980–2014) mean monthly rainfall measured at Hagere Selam. Error bars indicating the standard error of the mean.

haresha' pulled by a pair of oxen with tillage frequency up to four times per season. The main crops are cereals, legumes and vegetables, which are grown primarily during the main rainy season on a rotational basis. Free stubble grazing in croplands is common during dry seasons. Grazing pressure on rangeland is very high during the rainy season and hence vegetation cover is very low [7].

Methodology

Runoff plots and their characteristics

Rainfall-runoff data were collected with runoff plots installed at several sites in the Mayleba catchment during the main rainy season (July to September) of 2010, 2011 and 2012. The runoff plots were located at three cropland and three rangeland sites, corresponding to gentle (5%), medium (12%) and steep (16%) slopes (Fig. 1b; [7]). During plot sites selection, similarity in soil depths among sites on the different land use types and hillslope gradients were carefully considered. At each site in rangeland, four runoff plots were installed: a control plot, a plot treated with stone bunds, a plot treated with soil trenches and a plot treated with both stone bunds and soil trenches (Table 1; Fig. 3). Similarly, three runoff plots were installed at each site in cropland: a control plot, a plot treated with stone bunds and a plot treated with both stone bunds and soil trenches (Table 1). Stone bunds or trenches are the commonly installed SWC structures by the local communities and widely applied in cropland and rangeland throughout the broader study region. Three to seven SWC structures were installed per plot, depending on site slope gradient (Table 1). This density of SWC structures is based on local guidelines [57] and can therefore be considered representative for the region.

The runoff plots were bounded with soil bunds (45 cm wide and 30 cm high) that were compacted during installation. The plot boundaries were inspected daily for any damage (e.g. due to trampling by grazing cattle, rainfall or runoff erosion) to avoid leakages in and out of a plot [7]. Any observed damage was immediately repaired. To avoid plot boundary damage, compacted soil bunds were also covered with stone riprap. The runoff plots were also protected from upland run-on using diversion ditches that drained run-on to the sides of the plots site. At the bottom end of each plot, a 17 m^3 collector trench was installed and lined with a geomembrane to collect all the runoff and sediment.

Vegetation and surface rock fragment cover were measured at each plot. This was done weekly using the point count method along a line transect [7]. The soil type at each plot site was determined from the soil profile at the collector trench based on the FAO guidelines for soil profile description [58] and confirmed against the soil map of the catchment [54]. In addition composite topsoil samples were collected from each plot to analyze soil texture using the Hydrometer method and to determine soil organic carbon content by the wet oxidation [59]. Furthermore, soil infiltration rates at each measuring site were measured with a double ring infiltrometer. More detailed information on the soil characteristics of the runoff plots as well as further technical details on the SWC structures (Fig. 3) are reported by Taye et al. [7].

Table 1
Runoff plots characteristics: land use, plot area (all plots having width of 10 m and length that varies from 60 to 100 m), slope gradient (SG), number of soil and water conservation (SWC) structures per plot, surface soil texture (ca. 15 cm) depth, bulk density and rock fragments cover. NA is not applicable.

Land use	Plot treatment	Plot area (m^2)	SG (%)	Number of SWC structures	soil texture	Bulk density (g/cm^3)	Rock fragment cove (%)
Rangeland (RL)	Control	600	5	NA	Clay	1.3	8
	Stone bunds	600	5	3	Clay	1.4	6
	Soil trenches	600	5	3	Clay	1.5	7
	Stone bunds with soil trenches	600	5	3	Clay	1.5	9
	Control	600	12	NA	Clay loam	1.4	23
	Stone bunds	600	12	5	Clay loam	1.5	33
	Soil trenches	600	12	5	Clay loam	1.3	20
	Stone bunds with soil trenches	600	12	5	Clay loam	1.4	26
	Control	630	16	NA	Clay	1.6	38
	Stone bunds	630	16	7	Clay	1.6	37
	Soil trenches	630	16	7	Clay	1.4	29
	Stone bunds with soil trenches	630	16	7	Clay	1.5	30
Cropland (CL)	Control	1000	5	NA	Clay	1.0	6
	Stone bunds	1000	5	5	Clay	1.2	5
	Stone bunds with soil trenches	1000	5	5	Clay	1.1	4
	Control	910	12	NA	Clay loam	1.1	19
	Stone bunds	910	12	7	Clay loam	1.0	20
	Stone bunds with soil trenches	910	12	7	Clay loam	1.1	22
	Control	770	16	NA	Clay loam	1.0	25
	Stone bunds	770	16	7	Clay loam	1.2	28
	Stone bunds with soil trenches	770	16	7	Clay loam	1.3	26

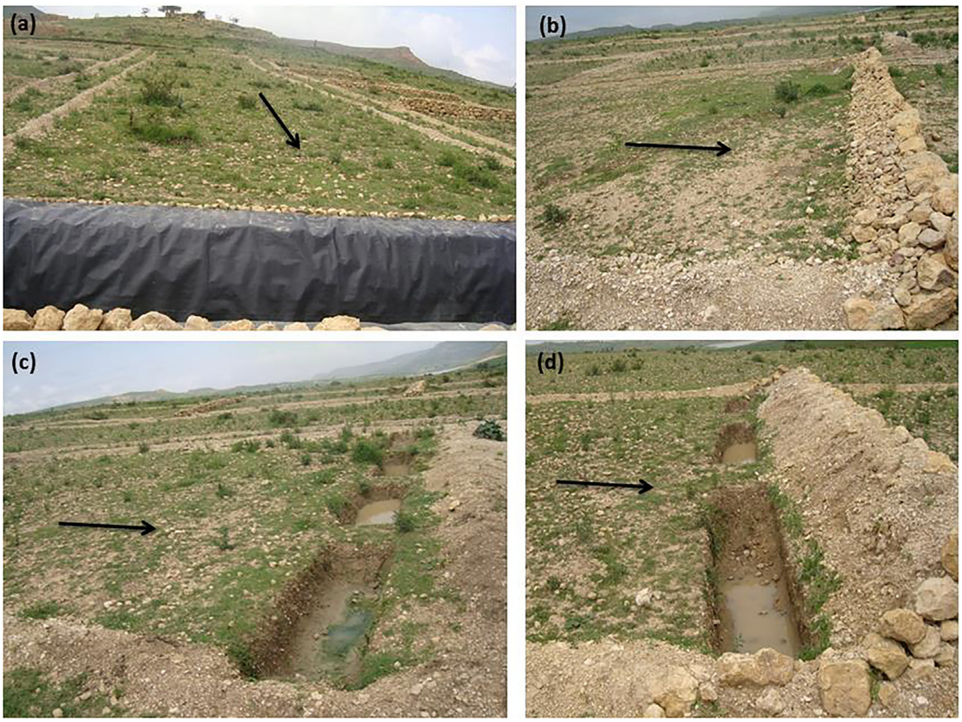

Fig. 3. Illustration of SWC structures in rangeland: (a) control plot, (b) stone bund, (c) soil trenches and (d) stone bund with soil trenches. Arrow within each plot indicates runoff direction.

Rainfall-runoff measurement

The daily rainfall depth at each site was measured with manual rain gauges (Fig. 1b). The corresponding runoff depth from each plot was also measured daily. Both daily rainfall and runoff depths were measured and recorded at 8:00 AM. To quantify runoff depth, the water depth in the collector trench was measured at five permanent and fixed measuring points on the runoff collector. The average value of measured water depths was then converted into a runoff volume, using depth-volume relationships that were established for each collector trench and each rainy season to account for any changes in the geometry of a collector during off-seasons [45]. The runoff depth (mm) for each plot was then calculated by dividing the recorded runoff volume by the corresponding plot area. The rainfall depth that directly fell on the collector trench was subtracted from the runoff depth. Since most rains (>80%) falls in afternoon and evening, underestimations of the runoff volume due to evaporation between the time of rainfall and the time of measurement were negligible [7].

The curve number method

The runoff Curve Number (CN) method also known as the Hydrological-Soil-Cover Complex Model was originally introduced by the USDA Soil Conservation Service (SCS) now the Natural Resources Conservation Service (NRCS). The method is widely applied for rainfall-runoff hydrology (e.g., [26,42,60,61]). It was originally designed to estimate surface runoff volume from small to medium-sized and ungauged agricultural catchments to help conservation planning [61,62]. Since its inception in 1950's, the CN method has evolved through several user improvements, modification and new applications of the method were also introduced [29,41,63–65]. The core idea of the model is the assignment of CN values that describe the runoff production of an area. Possible CN values vary from 0 (no runoff production from any rainstorm i.e. infinite catchment storage) to 100 (when all rains contribute to runoff for every rainstorm; [63]). Due to its simplicity, and limited input requirements, the method is integrated into several hydrological and soil erosion models to estimate surface runoff [34,66,36]. It is possible to obtain the CN values from tables [60] based on catchment characteristics such as land use, hydrological soil group (HSG; which depends on soil texture and minimum infiltration rates), land management and the antecedent soil moisture conditions (AMC) [67,42]. However, such CN values derived from NEH-Tables should be used as a guide [42] as the method is highly sensitive to the selected CN values. CN values calculated from locally measured rainfall-runoff data are overall more reliable and applicable for runoff estimation than those derived from NEH-Tables [26,30,42].

Overall, daily runoff depths are calculated based on the relations between measured daily rainfall depths and the soil water retention (i.e. initial abstraction and cumulative infiltration after runoff initiation (S)) as indicated in Eq. (1). This relation is based on a fundamental concept of a water balance which considers input (rainfall depths), outputs (runoff depths) and change in soil water retention or storage (S) [42,60,61,67]:

$$Q_p = \frac{(p - Ia)^2}{(p - Ia + s)} \tag{1}$$

With Qp daily runoff depth (mm/day), p the measured daily rainfall depth (mm/day), Ia the daily initial abstraction loss (mm/day) and S the maximum soil storage parameter (mm/day). This initial abstraction loss can be related to the maximum potential soil storage parameter (S) through the equation [42]:

$$Ia = \lambda S \tag{2}$$

The value of λ can vary between 0 and 1. Originally, λ was set equal to 0.2 (i.e., Ia = 0.2S). However, this value has been challenged by several authors (e.g., [42,43,66,26]). Most of these authors recommended λ values close to 0.05.

The relation between S and the Curve Number (CN) values is described as [42]:

$$CN = \frac{25400}{(254 + S)} \tag{3}$$

The original NEH-tables are based on an initial abstraction ratio of 0.2 and an average antecedent moisture condition i.e., AMCII. To facilitate conversion of CN-values for a λ-value of 0.20 ($CN_{0.2}$) to the corresponding CN-values for a λ-value of 0.05 ($CN_{0.05}$), a relationship was established between $S_{0.2}$ and $S_{0.05}$ [42]:

$$s_{0.05} = 2.255(S_{0.2})^{1.15} \tag{4}$$

Where: $S_{0.05}$ is the maximum soil retention potential when the initial abstraction ratio is 0.05 and $S_{0.2}$ is the maximum retention potential when the initial abstraction ratio is 0.2. The $CN_{0.05}$ values can be transformed to the corresponding $CN_{0.2}$ values using the equation with initial abstraction ratio of 0.2 ($CN_{0.2}$) [42]:

$$CN_{0.05} = 100/\left\{2.255[(100/CN_{0.2}) - 1]^{1.15} + 1\right\} \tag{5}$$

Determination of CN values for runoff plots based on the NEH-Tables

To assign CN values to the runoff plots based on the NEH-Tables, runoff plot surface characteristics were considered. These are land use types (cropland and rangeland), treatment practices such as grazed, contoured and combination of contoured and terraced, hydrological conditions and hydrological soil group (HSG). All rangeland plots were intensively grazed

Table 2
The number of rainfall events in different rainfall classes; the values in parenthesis indicate the number of rainfall events that generated runoff for control plots. RL is rangeland, CL is cropland

Land Use	runoff plots site	Seasons	Rainfall classes (mm/day) 0-10	10.1-20	20.1-84	Number of runoff events per season per plot
Rangeland	RL-Gentle	2010	22 (6)	6 (6)	6 (6)	18
		2011	34 (7)	7 (7)	5 (5)	19
		2012	14 (4)	13 (13)	15 (15)	32
	RL-Medium	2010	21 (6)	7 (7)	5 (5)	18
		2011	34 (8)	5 (5)	6 (6)	19
		2012	15 (6)	13 (13)	13 (13)	32
	RL-Steep	2010	26 (8)	6 (6)	4 (4)	18
		2011	30 (6)	8 (8)	5 (5)	19
		2012	17 (6)	10 (10)	14 (14)	30
Cropland	CL-Gentle	2010	32 (8)	7 (7)	4 (4)	19
		2011	37 (9)	5 (5)	5 (5)	19
		2012	24 (8)	6 (6)	12 (12)	26
	CL-Medium	2010	33 (7)	7 (7)	5 (5)	19
		2011	36 (9)	5 (5)	5 (5)	19
		2012	26 (9)	9 (9)	7 (7)	25
	CL-Steep	2010	34 (10)	5 (5)	3 (3)	18
		2011	37 (10)	3 (3)	6 (6)	19
		2012	25 (7)	10 (10)	7 (7)	24

throughout the year and hence the grazed option is used. All runoff plots in cropland were tilled on the contour, close-drilled with the seeds broadcasted during planting and crop rotation was also commonly practiced over the seasons. Therefore, a contoured option is used for control plots in cropland. In addition to contour ploughing practices, taking into account the effects of SWC structures on rainfall-runoff production is needed for treated cropland plots and hence the contoured and terraced option is applied [60]. But such option (grazed and terraced) option is not available for rangeland plots treated with SWC structures in the NEH–Tables [42]. The hydrological conditions of the runoff plots were determined as poor, fair or good based on field observation and recorded surface conditions (i.e., grazing intensity, status of measured vegetation cover and tillage) and conditions of the SWC structures. The HSG is based on soil texture (Table 1) and minimum or final infiltration rate (mm/h) measured at each site. Infiltration classes for HSG as proposed by Hawkins et al. [42] were used to classify soils of the studied sites into HSG. Using these inputs, the CN value corresponding to each plot was assigned by selecting the relevant value in the original NEH-Tables.

Application of CN method to plot data

Pooling of the rainfall-runoff data

The number of daily rainfall-runoff observations recorded for each plot during each rainy season is too small to calibrate and test runoff CN method (Table 2). Therefore, for each land use type (i.e. cropland and rangeland), the data was pooled according to slope gradient or decreasing effectiveness of SWC structures in reducing runoff production over time. For runoff plots on the same land use type and SWC treatments but with significant effects of slope gradient on runoff production and with relatively constant effectiveness of the SWC structures in reducing runoff over the three rainy seasons (cf. [45]), we pooled the daily rainfall-runoff data sets collected during the three rainy seasons (2010–2012). More specifically, this was done for the control plots and for the plots treated with stone bunds in both rangeland and cropland as well as for plots treated with stone bunds and soil trenches in cropland. For plots showing a significant decline in SWC structures effectiveness in reducing runoff production over the three seasons but with relatively small effects of slope gradients on runoff production within a specific season [45], we pooled the daily rainfall-runoff data collected for plots at gentle, medium and steep slope gradients for each season. More specifically, this was done for plots treated with soil trenches and stone bunds with soil trenches that were installed in rangeland. With this pooling scheme, the rainfall-runoff data collected from 21 large runoff plots over three seasons were grouped into 21 groups each consisting of 54 to 94 daily rainfall-runoff observations.

Determination of CN values: calibration and validation with Monte Carlo simulation

Using the pooled datasets (Section 2.5.1), a Monte Carlo simulation technique was used to draw random samples consisting of two thirds of the datasets for calibration and one third of the datasets for validation. For each group of pooled datasets (21 groups) sub-samples were drawn 200 times for each of the calibration and validation. Monte Carlo simulation, calibration and validation were conducted using Matlab® and Excel® 2013. In order to calibrate the CN values, the daily or event-based maximum retention potential (S; mm/day) was calculated using pooled datasets and for each of the 200 calibration sub-samples (two third of the pooled dataset). The initial abstraction ratio (λ) for North Ethiopian condition is reported to be 0.05 [16,43,24], therefore, the value of λ was set to 0.05. The 0.05 initial abstraction ratio also resulted into better rainfall-runoff fits with higher values of coefficient of determinations (R^2) for the different plots compared to the fits with 0.2 initial abstraction ratio using our dataset. In the three gorges area of China, Shi et al. [66] also found a value of 0.048 for initial abstraction ratio and significant improvement of runoff prediction using CN for $\lambda = 0.048$ compared to the traditional value $\lambda = 0.2$.

This maximum soil retention potential (S) was calculated for each of the daily measured rainfall-runoff depths using Eq. (6) for calibration datasets. This equation is derived for general λ values (e.g. $\lambda = 0.05$) which is different from the original value of 0.2 considered by SCS-CN method [42]:

$$S = \left[2\lambda P + Qo(1-\lambda) - \sqrt{\left\{[Qo(1-\lambda)]^2 + 4\lambda QoP\right\}}\right] / \left(2\lambda^2\right) \quad (6)$$

With: S is the maximum soil retention potential (mm/day), λ is the initial abstraction ratio (Ia/S), P is daily rainfall depth (mm/day) and Qo is daily measured runoff depth (mm/day) corresponding to the daily rainfall depth. For the S value calculated using the original initial abstraction ratio $\lambda = 0.2$, a conversion can be applied to calculate the corresponding S value for $\lambda = 0.05$ [42].

An average value of S was then calculated considering all the daily rainfall-runoff observations for the calibration datasets of each plot and assigned to a cell in spreadsheet for optimization using the solver function in Excel after having the output exported to Excel from Matlab®. An optimization was done to adjust (optimize) the value of lumped S by minimizing the sum square differences between the measured (Qo) and predicted (Qp) daily runoff depths of the calibration datasets. During the optimization process, each of the daily potential maximum retention value is adjusted and hence the corresponding fitted CN value of the calibration datasets. The optimized average "S" is then used to estimate runoff depth in Eq. (1) for each of the daily rainfall-runoff data of the validation (one third) of datasets. Moreover, based on the observed daily runoff and predicted daily runoff depths, the root mean square error (RMSE) and Nash-Sutcliffe model efficiency [68] were calculated to evaluate the CN method for the validation datasets. Root mean square error (RMSE) is calculated for each group of validation dataset in Eq. (7):

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{\left(Q_{oi} - Q_{pi}\right)^2}{n}} \quad (7)$$

With: $Q_{o\,i}$ is the *i*th observed runoff depth (mm/day), $Q_{p\,i}$ is the *i*th predicted runoff depth (mm/day) and n is the number of rainfall-runoff observations used. Model Efficiency (ME) is for each of the calibration and validation dataset is calculated based on Nash-Sutcliffe model efficiency (ME; [68]).

$$ME = 1 - \frac{\sum_{i=1}^{n} \left(Q_{oi} - Q_{pi}\right)^2}{\sum_{i=1}^{n} \left(Q_{oi} - Q_{ave}\right)^2} \quad (8)$$

With: Q_{ave} is the average observed runoff depth (mm/day), ME values between 0 and 1 indicating that the model is acceptable for a catchment models [69]. The closer the value of ME to 1 means that model is perfect, while negative values indicated prediction is very poor and using single average value provide a better estimate than model predictions [67].

Determination of Antecedent Moisture Condition (AMC) for the runoff plots

The SCS-CN method specifies three distinct antecedent soil moisture conditions (AMC) which play an important role in the selection of the CN values from NEH-Tables [70]. The AMC i.e., soil moisture conditions before an event, can significantly influence the rainfall-runoff production by determining the fraction of the rainfall depth that will be absorbed by the soils before and after runoff initiation [60,70]. Three antecedent moisture conditions were established based on the cumulative rainfall depth recorded during five days prior to a runoff producing event. The AMCII is accepted as a reference representing an average soil moisture condition for runoff production. AMCI and AMCIII represent dry and wet conditions with low and high runoff potentials respectively [71]. For the studied plots, the AMC was determined based on the rainfall depth recorded during the 5-days preceding runoff event (P_5; [42]) as:

AMC I: if $P_5 < 12.7$ mm

AMC II: if 12.7 mm $< P_5 <$ 27.9 mm

AMC III: if $P_5 > 27.9$ mm

Partitioning our rainfall-runoff datasets into AMCI, AMCII and AMCIII conditions based on P_5, indicates that AMCIII was the dominant condition for the measuring seasons covering 65% of the rainfall-runoff events. Therefore, the calculated CN values in this paper correspond to this dominant AMC (i.e., AMCIII). Different conversion procedures exist to convert the CN values from AMCII to AMCI or AMCIII [42,72]. In this study the relation proposed by Chow et al. [72] was used to convert CN values obtained based on NEH-Tables to CN values with AMCII i.e., the actual condition.

$$CN(III) = 23CN(II)/[10 + 0.13CN(II)] \quad (10)$$

Table 3
CN values for plots with and without SWC structures derived from the NEH-Tables for AMCII and λ=0.2 for land uses: RL is rangeland, CL is cropland. SWC treatments: CO is control, SB is stone bunds, TR is soil trenches and SBT is stone bunds with soil trenches at G (gentle), M (medium) and Steep (S) slope gradient sites.

Plot code	Treatment	Hydrological Condition	Soil texture	HSG	CN (NEH-Tables)
CL-CO-G	Contoured	Poor	Clay	D	85
CL-CO-M	Contoured	Poor	Clay Loam	C	83
CL-CO-S	Contoured	Poor	Clay Loam	C	83
CL-SB-G	contoured and terraced	Good	Clay	D	81
CL-SB-M	contoured and terraced	Good	Clay Loam	C	78
CL-SB-S	contoured and terraced	Good	Clay Loam	C	78
CL-SBT-G	contoured and terraced	Good	Clay	D	81
CL-SBT-M	contoured and terraced	Good	Clay Loam	C	78
CL-SBT-S	contoured and terraced	Good	Clay Loam	C	78
RL-CO-G	Grazing	Poor	Clay	D	89
RL-CO-M	Grazing	Poor	Clay Loam	C	86
RL-CO-S	Grazing	Poor	Clay	D	89
RL-SB-G	Grazing	Fair	Clay	D	84
RL-SB-M	Grazing	Fair	Clay Loam	C	79
RL-SB-S	Grazing	Fair	Clay	D	84
RL-TR-2010	Grazing	Good	Clay	D	80
RL-TR-2011	Grazing	Fair	Clay	D	83
RL-TR-2012	Grazing	Poor	Clay	D	88
RL-SBT-2010	Grazing	Good	Clay	D	80
RL-SBT-2011	Grazing	Fair	Clay	D	83
RL-SBT-2012	Grazing	Fair	Clay	D	88

Results and discussion

CN values derived from NEH-Tables

Table 3 presents the land use types, plot treatments, hydrological condition, HSG and the CN values derived for the runoff plots using the NEH-Tables. The soil textural classes of the studied sites are mainly clay and clay loam (Table 3). On the basis of soil textural classes and measured minimum soil infiltration rates, the HSG fall into the groups C and D indicating that most sites with soil group D having a high runoff production potential [42]. The CN values derived from the NEH-Tables ranged from 78 to 89 (Table 3). These CN values indicate a high runoff production for the treated and untreated plots of both land use types. In contrast, runoff depths from plots treated with SWC structures are significantly smaller compared to runoff depths from the corresponding untreated plots [7]. This clearly shows that, the effects of the different SWC structures on rainfall-runoff production as applied in Tigray (Ethiopia) are not represented by the NEH-Tables. The CN values derived from the NEH-Tables correspond to AMCII and λ value of 0.2 (Table 3). In order to compare the CN values deduced from NEH-Tables and those calculated for AMCIII and initial abstraction ratio $\lambda = 0.05$ using the measured rainfall-runoff data, the derived CN values (using the NEH-Tables) should be converted to AMCIII and initial abstraction ratio ($\lambda = 0.05$; Table 4). The results shown in Table 4, column 9 for NEH-Tables derived CN-values and column 10 for calculated CN values (based on measured rainfall-runoff data) clearly indicate that the CN values deduced from the NEH-Tables are consistently larger (by 21% on average) compared to those calculated from rainfall-runoff datasets.

The implication of this is that CN values derived from the NEH-Tables overestimate runoff depths compared to the CN values calculated from measured runoff data. The difference between the two CN values is especially much larger for plots with SWC structures. This result highlights that depending on the type of SWC structures installed and land use type, calculated CN values (based on runoff plot data) for those SWC structures are more appropriate than those derived from NEH-Tables. Like our findings, Lian et al. [30] reported a clear differences between the calculated CN values and those derived from the NEH-table with the calculated values showing wider variations ranging from 12.8 to 97.45 compared to 36 to 91 for CN values derived from the NEH-tables in China.

Considering sensitivity of estimated runoff depths to the selected CN values [42], such differences between CN values derived from the NEH-table and those values calculated from measured rainfall-runoff data entail considerable errors in estimated runoff depth. This is in line with Teka [73] who also reported a runoff depth overestimation by 10.6% on average when using CN-values obtained from the NEH-Tables compared to those locally calibrated CN-values at sub-catchment scale. Previous studies (e.g., [74]), reported that a decrease in the CN values by 10% leads underestimation of surface runoff depth by 45% while increase in CN value by 10% leads to an overestimation of surface runoff depth by up to 55%. Soulis and Valiantzas [26] also showed reasonable accuracy of the CN method when calibrated with measured rainfall-runoff data as compared to values derived from NEH-Tables.

Table 4
Transformation of the CN values from initial abstraction ratio ($\lambda = 0.2$) and AMCII from NEH-Tables (Table 3) to CN values with initial abstraction ratio ($\lambda = 0.05$) and AMCIII (column 9). Column 10 provides calculated CN values based on measured rainfall-runoff data. SG is slope gradients, HSG is hydrological soil group, $CN_{0.2}$ is the curve number values at initial abstraction ratio ($\lambda = 0.2$) and $CN_{0.05}$ is the CN values at initial abstraction ratio of ($\lambda = 0.05$)

Land use	SG (%)	Actual treatment	Treatment (NEH)	Hydrological condition	HSG	$CN_{0.2}$ AMCII	$CN_{0.05}$ AMCII	$CN_{0.05}$ AMCIII	$CN_{0.05}$ AMCIII
CROPLAND	5	Control	Contoured	Poor	D	85	76.5	88.2	78
	12	Control	Contoured	Poor	C	83	73.3	86.3	70
	16	Control	Contoured	Poor	C	83	73.3	86.3	68
	5	Stone bunds	Contoured and terraced	Good	D	81	70.1	84.4	72
	12	Stone bunds	Contoured and terraced	Good	C	78	65.5	81.4	61
	16	Stone bunds	Contoured and terraced	Good	C	78	65.5	81.4	60
	5	Stone bunds with soil trenches	Contoured and terraced	Good	D	81	70.1	84.4	52
	12	Stone bunds with soil trenches	Contoured and terraced	Good	C	78	65.5	81.4	38
	16	Stone bunds with soil trenches	Contoured and terraced	Good	C	78	65.5	81.4	34
RANGELAND	5	Control	Grazing	Poor	D	89	83.1	91.9	91
	12	Control	Grazing	Poor	C	86	78.2	89.2	87
	16	Control	Grazing	Poor	D	89	83.1	91.9	88
	5	Stone bunds	Grazing	Fair	D	84	74.9	87.3	81
	12	Stone bunds	Grazing	Fair	C	79	67.1	82.4	82
	16	Stone bunds	Grazing	Fair	D	84	74.9	87.3	82
	5,12,16	Soil trenches	Grazing	Good	D	80	68.6	83.4	65
	5,12,16	Soil trenches	Grazing	Fair	D	83	73.3	86.3	68
	5,12,16	Soil trenches	Grazing	Poor	D	88	81.4	91	87
	5,12,16	Stone bunds with soil trenches	Grazing	Good	D	80	68.6	83.4	51
	5,12,16	Stone bunds with soil trenches	Grazing	Fair	D	83	73.3	86.3	48
	5,12,16	Stone bunds with soil trenches	Grazing	Fair	D	88	81.4	91	70

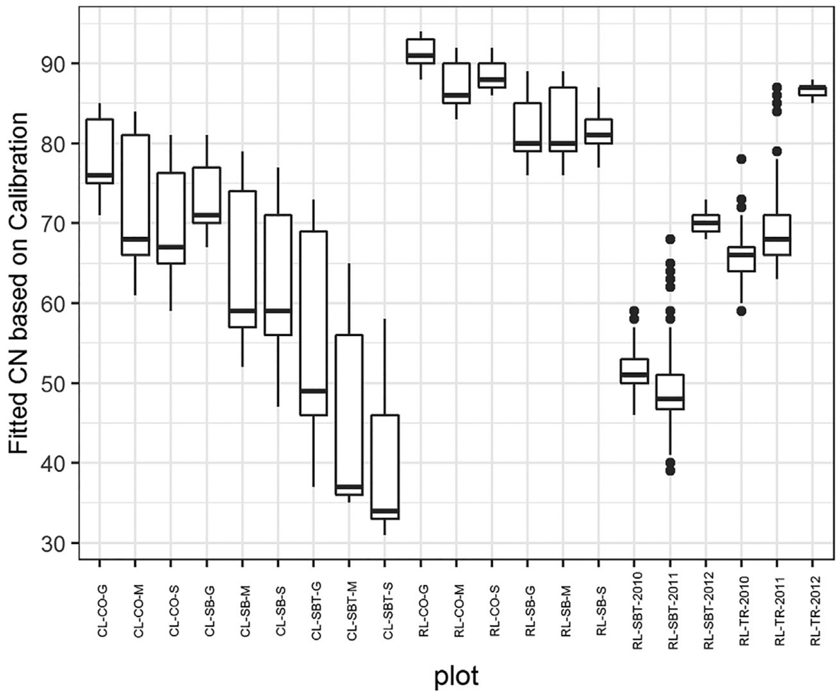

Fig. 4. CN fitted for calibration based on the 200 alternative sub-samples taken with the help of Monte Carlo simulation and consisting of 2/3 dataset. Dark line in the boxes indicating the median CN value and dark circles indicating outliers.

CN values calculated using measured rainfall-runoff data

Calculated CN values based on measured rainfall-runoff data for runoff plots with and without SWC structures are reported in Table 5. The CN values were calculated for the calibration i.e. 2/3 of pooled datasets (Table 5). Based on the calibration dataset ($n = 200$), the median CN values for the plots in both land use types range from 34, for a plot treated with stone bunds and trenches in cropland, to 91 for a control plot in rangeland (Table 5, Fig. 4). This wide range in calcu-

Table 5
CN0.05 values analyzed for pooled rainfall-runoff observations (fit with all data) and the 200 alternative sub-sample for calibration, number of plot year (PY) number of rainfall-runoff observations (n), maximum soil retention parameter (S) root mean square error (RMSE) and model efficiency (ME). 200 subsamples consisting 2/3 for calibration and 1/3 for cross-validation were random drawn from the data using a Monte Carlo simulation. The values in parenthesis represent the corresponding median.

			Fit with all data				**Fit based on calibration 2/3 of n**				**Fit based on validation 1/3 of n**	
Plot Code	PY	n	S	CN	RMSE	ME	S	CN	RMSE	ME	RMSE	ME
CL-CO-G	3	65	72	78	3.1	0.50	45–104 (80)	71–85 (76)	1.21–3.79 (3.10)	0.36–0.88(0.50)	1.37–6.38(3.38)	-0.49–0.77(0.28)
CL-CO-M	3	63	181	70	3.31	0.11	84–162 (120)	61–84 (68)	1.67–3.95 (3.34)	-0.12–0.72(0.19)	1.57–7.78(3.50)	-2.40–0.64(-0.46)
CL-CO-S	3	61	120	68	3.13	0.32	60–177 (125)	59–81 (67)	1.19–3.67 (3.18)	0.01–0.89(0.35)	1.71–7.94(3.25)	-2.75–0.58(-0.07)
CL-SB-G	3	63	99	72	2.34	0.61	60–125 (104)	67–81 (71)	1.15–2.82 (2.19)	0.34–0.82(0.64)	1.17–4.67(2.68)	-0.22–0.69(0.36)
CL-SB-M	3	63	162	61	2.67	0.03	68–234 (177)	52–79 (59)	1.45–3.14 (2.68)	-0.21–0.55(0.07)	1.23–7.09(2.74)	-3.36–0.32(-0.57)
CL-SB-S	3	61	169	60	2.72	0.11	76–286 (177)	47–77 (59)	1.29–3.19 (2.59)	-0.35–0.81(0.17)	1.39–7.17(3.14)	-5.48–0.36(-0.59)
CL-SBT-G	3	60	234	52	2.52	0.36	94–432 (264)	37–73 (49)	0.85–3.12 (2.34)	-0.81–0.77(-0.35)	1.15–6.8(2.94)	-17.96—0.07(-0.75)
CL-SBT-M	3	62	414	38	1.14	0.56	137–472 (432)	35–65 (37)	0.70–1.29 (1.10)	-1.76–0.002(-0.36)	0.79–4.69(1.21)	-12.46—0.82(-3.01)
CL-SBT-S	3	60	493	34	0.98	0.60	184–565 (493)	31–58 (34)	0.65–1.12 (0.93)	-2.35–0.03(-0.44)	0.62–3.60(1.10)	-11.53—0.65(-2.39)
RL-CO-G	3	69	25	91	5.08	0.49	16–35 (25)	88–94 (91)	2.46–6.14 (5.53)	0.17–0.87(0.45)	1.87–9.06(4.33)	-0.85–0.90(0.49)
RL-CO-M	3	66	38	87	5.4	0.23	22–52 (41)	88–92 (86)	2.64–6.57 (5.87)	-0.27–0.79(0.15)	3.13–10.26(4.56)	-2.15–0.76(0.28)
RL-CO-S	3	66	35	88	4.41	0.44	22–41 (35)	86–92 (88)	2.58–5.27 (4.73)	-0.04–0.78(0.41)	2.58–7.58(3.86)	-0.89–0.86(0.47)
RL-SB-G	3	70	60	81	4.83	0.04	31–80 (64)	76–89 (80)	2.61–5.82 (5.12)	-0.54–0.65(-0.12)	2.45–9.28(4.43)	-2.37–0.69(-0.01)
RL-SB-M	3	69	56	82	5.02	0.07	31–80 (64)	76–89 (80)	2.58–5.97 (5.38)	-0.40–0.72(-0.03)	2.86–10.57(4.57)	-2.61–0.67(0.14)
RL-SB-S	3	67	56	82	4.01	0.28	38–76 (60)	77–87 (81)	2.17–4.62 (3.99)	-0.16 0.73(0.30)	2.66–3.36(4.09)	-1.32–0.70(0.13)
RL-TR-2010	3	54	137	65	2.79	0.42	72–177 (131)	59–78 (66)	2.11–3.39 (2.82)	-1.46–0.25(-0.36)	1.27–4.55(2.82)	-5.95–0.33(-0.84)
RL-TR-2011	3	57	120	68	4.35	0.42	38–149 (120)	63–87 (68)	2.01–5.20 (4.25)	0.03–0.79(0.46)	1.96–13.13(4.66)	-2.26–0.78(0.23)
RL-TR-2012	3	94	38	87	2.95	0.73	35–45 (38)	85–88 (87)	2.02–3.45 (2.97)	0.59–0.87(0.72)	1.75–4.49(2.93)	0.29–0.89(0.73)
RL-SBT-2010	3	54	244	51	1.41	1.77	177–298 (244)	46–59 (51)	1.15–1.63 (1.41)	-2.48–0.86(-1.74)	0.81–1.91(1.47)	-7.27–0.04(-2.06)
RL-SBT-2011	3	57	257	48	2.08	0.42	120–397 (275)	39–68 (48)	0.92–2.42 (2.02)	-1.15–0.81(0.50)	1.22–7.26(2.32)	-7.70–0.75(-0.49)
RL-SBT-2012	3	94	109	70	1.84	0.54	94–120 (109)	68–73 (70)	1.18–2.12 (1.83)	0.05–0.84(0.54)	1.24–3.05(1.88)	-0.96–0.88(0.52)

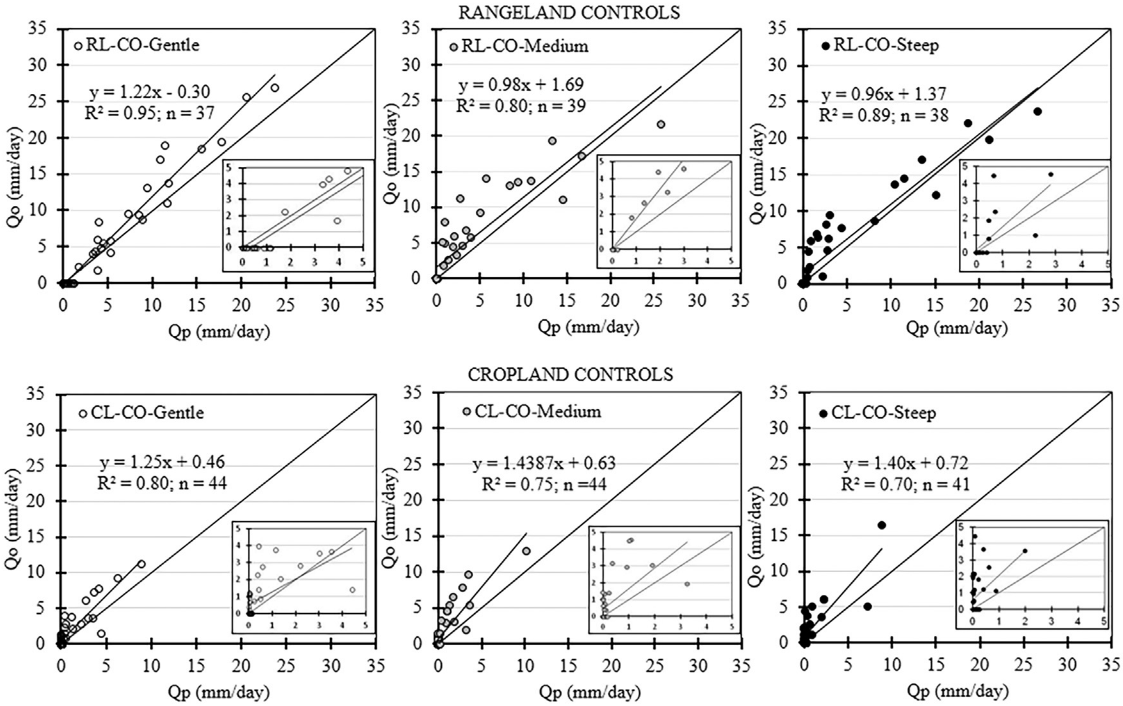

Fig. 5. The observed (Qo) versus predicted (Qp) runoff depths (mm/day) for control plots (CO) in rangelands (RL) and croplands (CL) a random selected example for cross-validation.

lated CN values is attributed to the effects of land use types, slope gradient and SWC structures. Compared to the plots with SWC structures, control plots showed large median CN values that range from 67 to 91, with the control plots in rangeland having larger median CN values compared to the corresponding control plots in cropland (Table 5). Along the same lines, Descheemaeker et al. [43] reported a high variation in CN values (29 to 97) using plot data in Tigray for the same AMC and initial abstraction ratio (i.e., AMCIII and $\lambda = 0.05$). They attributed this variation to land use type and vegetation cover. The median CN values for control plots in rangeland (86 to 91) are like those (86 to 97) reported by Descheemaeker et al. [43] for the same land use and region.

For plots treated with SWC structures, the median CN values were consistently larger for rangeland plots than for cropland plots (Table 5). For instance for plots treated with stone bunds in rangeland, the median CN value ranges from 80 to 81, while this value ranges from 56 to 71 for the corresponding cropland plots treated with stone bunds. Plots treated with stone bunds and soil trenches installed in cropland had the smallest median CN value ranging from 34 to 49. The SWC structures in these plots remain very effective in reducing runoff during the three measuring seasons and the CN values vary over a wide range. Rangeland plots treated with soil trenches and stone bund with soil trenches show highly variable CN values in 2010 and 2011, however, with a decreasing effectiveness of these structures in 2012, their corresponding CN values become remarkably stable (Fig. 4). For all plots in both land use types, the CN value decreases with increasing slope gradient (Fig. 4) indicating decreasing runoff production on steeper slopes. This is due to a corresponding increase in surface rock fragment cover [7]. In contrast Mishra et al. [75] indicated systematic increased in CN values with increasing slope gradients from 1% to 5% for maize and sugarcane fields in Roorkee, Uttarakhand (India).

The observed and predicted runoff depth fits better for the plots in rangeland than the corresponding plots in cropland (Fig. 5). As shown in Table 5, the median model efficiency (ME) for plots in cropland ranges from (-3.01 to 0.28) with 78% of the plots having negative model efficiency for the validation. Rangeland plots had (-2.03 to 0.73) median ME values with 33% of the plots having negative model efficiency based on the validation. Taye et al. [7] have shown that runoff production in the study area depends on land use type. The difference in runoff production and hence the CN values for the different plots is explained by their differences in land use type and SWC structures. The two land use types are different in terms of vegetation cover and management practices such as tillage practices in cropland and intense grazing in rangeland [7] which in turn affects runoff production. The control plots and plots with stone bunds in rangeland do have high and more stable CN values (Fig. 4). For plots with a small runoff production potential (e.g. plots treated with soil trenches in rangeland and stone bunds with soil trenches in both land use types), the CN values remain low and highly variable. For a high runoff producing control plots in rangeland, predicted runoff depths are related to the observed runoff depth with R^2 values ranging from 80% to 95% compared to a relatively low runoff producing control plots in cropland with R^2 values ranging from 70% to 80% (Fig. 5). Similarly, Descheemaeker et al. [43] reported that the performance of the curve number method is related to runoff production. They indicated that more reliable CN values were obtained for high runoff producing overgrazed rangelands compared to adjacent exclosures and natural church forest both with high vegetation cover percentage and low runoff production potentials. Along the same lines Sultan et al. [44] also reported a more accurate runoff prediction with the CN method for untreated non-agricultural lands compared to plots treated with SWC structures in a tropical humid climate of Ethiopian highlands.

It is worth mentioning that in other catchments, close to the study area, a combination of geomorphology, geology and land use land cover type favors rainwater infiltration and hence development of localized shallow groundwater and springs. For instance, Walraevens et al. [76] considered a highland plateau i.e., a relatively gentle sloping area, composed of Trap basalts that may favor rapid infiltration and development of shallow groundwater due to deep and wide cracks formed in Vertisols during extended dry periods. Such shallow groundwater is reported to significantly increase surface runoff as soil infiltration is reduced [76]. Instead, the Mayleba catchment, in particular the location of the runoff plots, has steep slopes and shallow soils resting on a continuous hard limestone rock which induced rapid surface and subsurface drainage. To the best of our knowledge and based on field observations made during the three-year monitoring period, the presence of such shallow groundwater was never observed at the location of the runoff plots. This can be attributed to: (1) shallow soils underlined by a continuous hard rock and limited infiltration due to overgrazing, trampling compaction and rapid surface and subsurface drainage on sloping land; (2) bare land without vegetation cover which promotes more runoff than infiltration and groundwater recharge; (3) location of runoff plots on limestone formation, as this is the dominant geology in the catchment and in the region, whereas the presence of shallow groundwater and seasonal springs is historically reported in the Maylaba catchment only around the contact between the basalt and the top of sandstone formations (e.g., [54]); (4) farmers of the study area use hand-dug wells for local scale and private land irrigation, such wells including those located in the valley bottom are deep (up to 10 m).

Historical deforestation and land degradation in the Mayleba catchment, combined with intense rainfall, reduced soil infiltration rates and recharge to groundwater while increasing surface runoff. On the other hand, enhanced infiltration, increased pore water pressure and localized landslides have been reported on slopes of Amba Raesat at Mayleba catchment where exclosures are located on Agula shale and Marl formations [77]. The implementation of exclosures increases vegetation cover which reduced runoff and enhanced infiltration. Restricted redistribution of water in the soil profile and limited percolation due to impermeable layer increased hydrostatic pressure and triggered landslides as reported by Woldearegay et al. [77]. Therefore, the combination of land use, slope and geological formation at the runoff plot sites promoted more runoff than infiltration and groundwater recharge.

SWC structures and CN method

For plots treated with stone bunds (Fig. 6a), runoff depth is underestimated with the CN methods for both land use types. The same holds for plots treated with soil trenches and stone bunds with soil trenches in rangeland (Fig. 6b). For plots treated with soil trenches and stone bunds with soil trenches installed in rangeland, the performance of the CN method was poor during the first season following their installation (Fig. 6b). This is shown by negative model efficiencies based on validation (Table 5) and also poor fits of the regression between the observed and predicted runoff depth (Fig. 6b). However, with a decreasing effectiveness of these SWC structures during the second (2011) and third (2012) monitoring seasons, the performance of the CN method for runoff prediction significantly improved (Table 5; Fig. 6b). For example, based on validation, plots treated with soil trenches in rangeland had median model efficiency (ME) value of -0.84 in 2010 which increased to 0.73 in 2012. The median model efficiency for plots treated with stone bunds and soil trenches in rangeland was -2.06 in 2010 and improved to 0.52 in 2012 for the validation (Table 5). This indicates that runoff prediction with the CN method is more reliable for conditions of high runoff production compared to conditions of low runoff production. In contrast plots with stone bunds and trenches installed in cropland are the most effective in reducing runoff and their effectiveness remains high throughout the measuring seasons. During the seasons model efficiencies for these plots remain negative and highly variable (Table 5, Fig. 7). In line with this, Peng and You [78] reported that with the application of the SCS-CN method a remarkable runoff simulation efficiency has been achieved for areas having greater than 0.5 runoff coefficient in China.

Evaluation of the CN method

The model efficiencies for the CN methods for the different plots are reported based on the calibration datasets (Fig. 7a) and based on the validation (Fig. 7b). Different techniques are available to evaluate the performance of catchment models [69]. Our results show that based on the calibration datasets 33% (3 out of 9 plots) in cropland and 33% (4 out of 12) plots in rangeland had negative model efficiency (Table 5). The CN values calculated for the calibration datasets of a given plot varied over a wide range. The model efficiency is also negative and highly variable (Fig. 7a, b) for both calibration and validation. These unstable CN values and negative model efficiencies may suggest that the number of rainfall-runoff events used for calibration and validation could still be insufficient to obtain reliable and robust results. The stability of the CN values is very low and fluctuated over a wide range for specific plots (Fig. 4) which is most probably due to the low number of observations used to calibrate and validate the method. This variation is especially larger for plots with lower runoff production potential due to the implemented SWC structures. In addition to the limited number of observations, the CN method

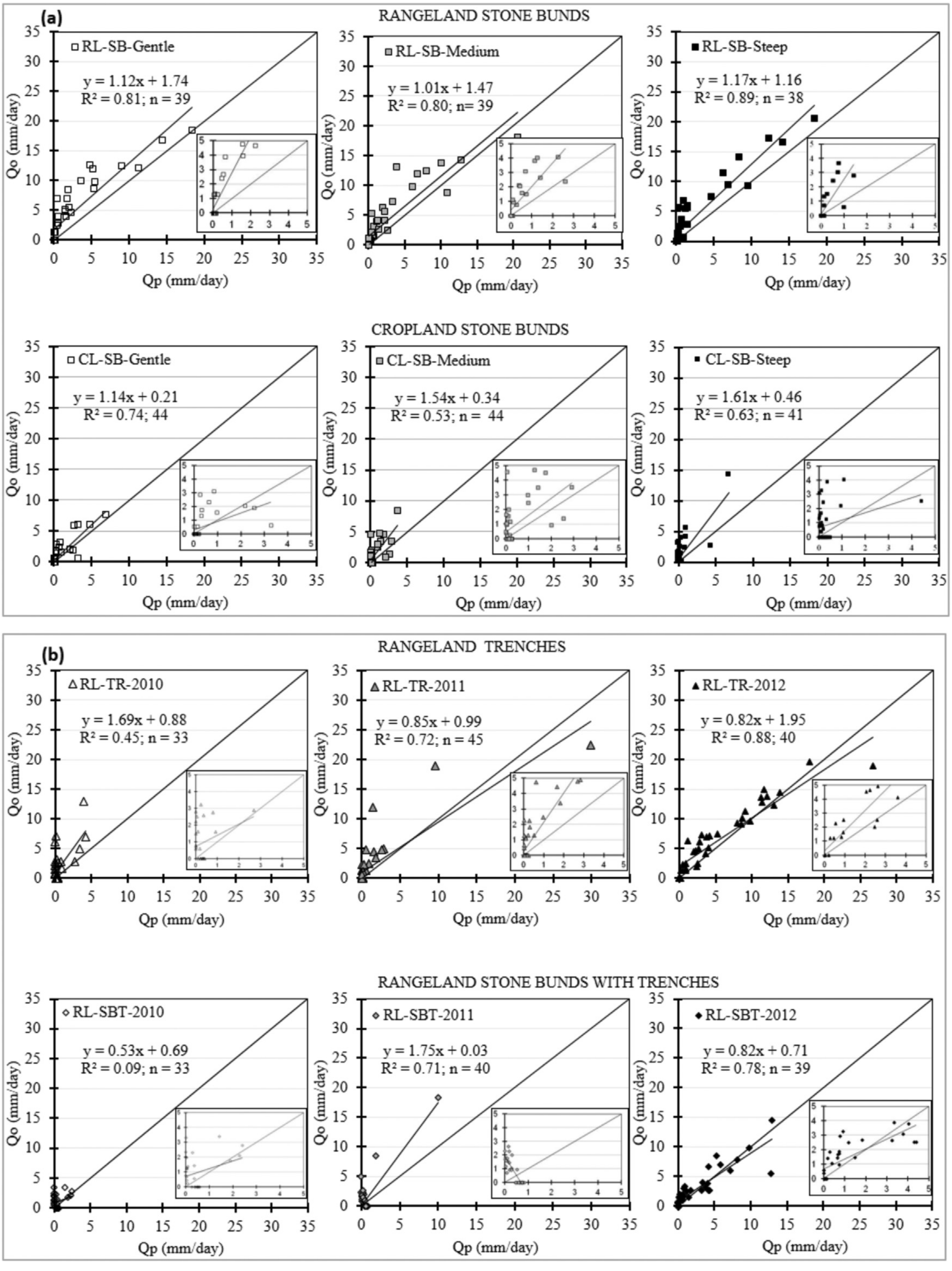

Fig. 6. Relation between the observed runoff depth (Q_o) and predicted runoff depth (Q_p) for (a) plots treated with stone bunds in rangeland (RL) and cropland (CL), and for b) rangeland plots treated with soil trenches and stone bunds with soil trenches.

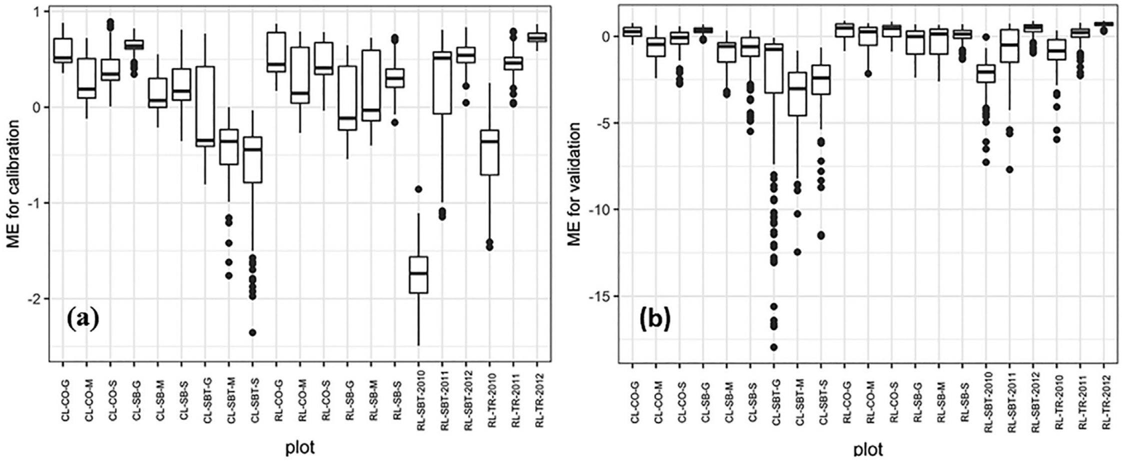

Fig. 7. Illustration of the median model efficiency (ME) based on 200 sub-samples of the pooled dataset (a) is for the calibration and (b) for validation datasets.

also suffer from capturing spatial and temporal variation related to rainfall and plots characteristics. For instance, different plots on the same land use type, slope gradient and rainfall depth tend to generate different runoff volume during the same season due to SWC treatments and spatial variation in vegetation or rock fragment cover. Moreover, the same amount of rainfall generated different volume of runoff from the same plot during different seasons due to temporal factor such as plot vegetation cover and antecedent soil moisture condition. The nature of rainfall such as intensity and frequency can also be an important factor controlling rainfall-runoff processes in this environment. These indicates that factors affecting the performance of the CN method are more complex [74,30,34] and might have contributed to the observed model efficiencies (Fig. 7a, b). In contrast to our results, Lian et al. [30] reported higher values of model efficiency for the CN method ranging from 0.76 to 0.98 for validation datasets in China on the selected large set of rainfall-runoff data.

The CN method was also applied in Ethiopian conditions as part of other hydrological and soil erosion models such as agricultural non-point source pollution (AGNPS) and general watershed loading function (GWLF) [79–81]. These studies reported mixed results of the application of the CN method and its performance for Ethiopian condition. Haregeweyn and Yohannes [79] reported a poor performance of the CN method, Mohammed et al. [81] reported that the CN method is highly sensitive while Legesse et al. [80] indicated the need for extensive calibration of the CN method. Our results also indicate that the performance of the CN method is mixed i.e., better performance in rangeland and plots with high runoff production and poor performance where runoff production is low due to SWC structures (Table 5). For plots with decreasing effectiveness of SWC structures in reducing runoff due to sediment infilling, the performance of CN method improved during the second- and third-year monitoring season as shown by the positive model efficiencies for both calibration and validation datasets (Fig. 7a, b).

Reliability of the results

Rainfall-runoff response is affected by both rainfall and catchment characteristics. These are important to understand runoff generation processes and the volume of runoff produced during a given rainfall event and from a particular catchment area [72,82]. The CN values reported in this study were calculated based on 2/3 of the dataset repeatedly sampled 200 times for the calibration. This sampling scheme with many different combinations of the rainfall-runoff depths and plot conditions (i.e., antecedent moisture condition (AMC) and vegetation cover) ensures that there was no bias of the calculated CN values towards large or small sets of rainfall-runoff depths during splitting of the data into calibration and validation datasets. Pooling the rainfall-runoff data has also resulted into a relatively large number of rainfall-runoff observations (Section 2.5.1) for the calibration and validation of the results though still insufficient. Considering the spatial heterogeneity of the rainfall and catchment characteristics and understanding the hydrological processes are important for a successful application of hydrological models [83]. The rainfall intensity is not accounted for by the CN method [42]. However, rainfall intensity and frequency could be the most important factor in relation to runoff production in arid and semi-arid area particularly for catchments with lower infiltration rates and poor vegetation cover [82]. This is also the case for the Mayleba catchment.

Our calculated CN values correspond to the dominant antecedent moisture conditions (AMCIII) and $\lambda = 0.05$ which is also recommended for the Ethiopian conditions [24,43,73]. Yuan et al. [84] also reported that the CN method is sensitive to the selected CN values and initial abstraction ratio, and they found optimized initial abstraction ratio that ranges from 0.01 to 0.53. They further recommended using smaller values of the initial abstraction ratio for a catchment with a large channel area and fine textured soils. Our runoff plots are characterized by fine textured soils (Table 1) composed of mainly clay and clay loam. Our field observation also revealed a rapid rainfall-runoff response particularly on rangeland plots and therefore, the selection of a low initial abstraction ratio i.e., $\lambda = 0.05$ is appropriate.

Reported CN values from plots treated with different SWC structures and slope gradients should be used with caution when predicting surface runoff at the catchment scale. Our results clearly show that the CN values vary widely even at plot scale. Runoff prediction with the CN methods is less reliable for plots treated with the most effective SWC structures. Therefore, to apply plot results to catchment scale, conditions of the catchment with respect to factors affecting rainfall-runoff processes should be studied in detail before selecting appropriate CN values. Schmocker-Fackel et al. [85] indicated the relevance of mapping dominant runoff processes when linking hydrological responses from plot to catchment scale. Up scaling plot level rainfall-runoff information to catchment scale can have a significant level of uncertainty. This is because catchment scale heterogeneities such as soils, land use, vegetation, slopes, depressions, channels etc. cannot be fully represented by the runoff plots which is a limitation of plot-based studies when addressing catchment-scale hydrology. Dividing the catchment into grids of uniform hydrological behavior (i.e., hydrological response units) can be a valuable approach to reduce the limitations when applying plot level information to the catchment scale.

Conclusions

This study aimed at selecting and extracting CN values that can be applied for runoff estimation in semi-arid environments and from catchments with SWC structures installed. We derived CN values from the NEH-Tables for various runoff plots based on land use types, treatment, hydrological conditions and HSG. CN values were also calculated based on measured rainfall-runoff data from plots with and without SWC structures over three rainy seasons. The CN values derived from the NEH-Table clearly overestimate runoff production as these values are significantly larger than the calculated CN values by 21% on average. The calculated CN values vary over a wide range (34 to 91) in response to land use types, slope gradient and type of implemented SWC structures. For plots with a high runoff production potential, the CN values are more stable, and model efficiencies are also positive. However, for plots with low runoff production potential i.e. plots treated with stone bunds with soil trenches in rangeland and cropland and plots treated with soil trenches in rangeland, the CN values vary widely, and model efficiencies are also negative. With the decreasing effectiveness of these SWC structures in reducing runoff production over successive years due to sediment deposition, the application of the CN method is more reliable and CN values become more stable. The implementation of SWC measures in a catchment strongly affects its hydrological response and hence, hydrological models should account for the impacts of the SWC structures when planning and managing water resources. Apart from addressing local challenges related to water resources management, the results of this study have important implications towards achieving most of the continental development goals (the African's Union's Agenda 2063) and sustainable development goals (SDC).

Statement of declarations

We declare that this manuscript is our own work and not published elsewhere or submitted for consideration

Data availability

Datasets are available from the corresponding author by request.

Declaration of Competing Interest

We declare that there is no conflict of interest of authorship or financial

CRediT authorship contribution statement

Gebeyehu Taye: Visualization, Data curation, Formal analysis, Writing – original draft. **Matthias Vanmaercke:** Visualization, Data curation, Formal analysis. **Samuale Tesfaye:** Visualization, Data curation, Formal analysis. **Daniel Teka:** Visualization, Data curation, Formal analysis.

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