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Rainfall Erosivity Estimators for Application in Burundi

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ABSTRACT

In this paper, following the results of previous studies and using the monthly rainfall data of 13 sites in Burundi, a comparison between two different estimators (modified Fournier index *MFI* and F_F index) of the rainfall erosivity factor of the Universal Soil Loss Equation (USLE) was firstly developed. The theoretical relationships between *MFI* and the mean annual rainfall *P* and between F_F and *P* were tested by the available rainfall data. The constants K_m and *K*, linking *MFI* and F_F with *P*, were used to assess hydrological similitude with other geographical regions. Then, in order to predict the erosion risk corresponding to a climatic condition of given return period, the applicability of the Extreme Value Type 1 (EV1) probability distribution to the annual values of the $F_{a,j}$ index was tested by an at-site analysis. Finally, the descriptive ability of the EV1 distribution was investigated by a regional procedure.

1 | Introduction

Soil erosion is a global challenge, negatively impacting food productivity, water security and biodiversity and accelerated soil erosion is a major threat to soil (Borrelli et al. 2017). East Africa is particularly vulnerable to soil erosion due to steep topography, fragile soils and intense rainfall (Fenta et al. 2020).

Burundi is among the poorest and most densely populated countries in the world and its economy is mainly focused on the agricultural sector (Nkurunziza and Ngaruko 2002). Subsistence activities dominate farming and a small agricultural production (tea and coffee) is marketed and exported (Bundervoet et al. 2009). Notwithstanding the climate favours agricultural production, in the last decades land productivity appears to have decreased due to the increasing population pressure and related erosion processes (Beekman and Bulte 2012). In this social context, investments in soil and water bioengineering techniques and other soil conservation strategies could positively affect the reduction of soil erosion and the increase of soil fertility, improving the socio-economic conditions of the rural Burundian communities (Preti et al. 2025).

Burundi presents considerable climatic irregularities that have contributed to cause food shortages over recent decades (Batungwanayo et al. 2020). According to Fenta et al. (2017), Burundi is one of the Eastern African regions with the highest rainfall erosivity. In particular, the mean annual rainfall factor, *R*, of the USLE (Wischmeier and Smith 1978) is equal to 3970 MJ mm ha^{-1}h^{-1}yr^{-1}. Similar or also higher values are reported for Tanzania and South Sudan (3920–4340 MJ mm ha^{-1}h^{-1}yr^{-1}) but much smaller values are reported for other countries of the area such as Djibouti and Sudan (445–1440 MJ mm ha^{-1}h^{-1}yr^{-1}). According to the classification by Foster et al. (1981), rainfall erosivity in Burundi is not very high (i.e., *R* does not reach values close to 8000 MJ mm ha^{-1}h^{-1}yr^{-1}) but it is appreciably higher than moderate (2000 MJ mm ha^{-1}h^{-1}yr^{-1}). Soil water erosion is therefore a serious problem in Burundi. El-Hassanin et al. (1993) reported that muddying of runoff water lost from the highlands of Burundi is noticeable to the naked eye and also that steep slopes and inappropriate management practices enhance the erosiveness of running water and erodibility of Burundian soils.

In the period 1980–1990, some research on soil loss measurements at plot scale was developed by ISABU (Institut des Sciences Agronomiques du Burundi) (ISABU 1991) and Kaboneka et al. (2024) reported mean annual soil loss values of 200–400 t ha^{-1}yr^{-1}, that is, 20–40 times the tolerable soil loss according to accepted international criteria (Di Stefano and Ferro 2016).

According to Nijimbere and Lizana (2019), 64% of almost the entire Burundian territory is expected to experience a severe erosion. A recent investigation of the hydro-climatic impacts of climate change over Burundi indicates an increase in precipitation in the north and a decrease in the south (Rivas-López et al. 2022). This circumstance leads to the supposition that, in the near future, even the rainfall erosivity and its spatial distribution could change in the Burundian territory.

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978) is the most widely applied soil erosion model for estimating soil loss in agricultural lands. This empirically-based but theoretically supported (Ferro 2010) model continues to be a good "*compromise between applicability (in terms of required input data) and reliability of obtainable soil loss estimate*s" (Risse et al. 1993). The USLE uses the rainfall erosivity factor, R, to express at mean annual temporal scale the influence of climate on soil loss rate and it is a useful tool to identify areas with a high soil loss risk, in which soil conservation strategies should be applied (Aronica and Ferro 1997). The product of event rainfall kinetic energy, E, with the maximum 30-min rainfall intensity, I_{30}, is used to calculate the rainfall erosivity index R_e of a single rainstorm. Monthly and annual values of the rainfall erosivity factor are calculated as sums of R_e values corresponding to all erosive rainfall events during their corresponding period. According to the procedure by Wischmeier and Smith (1978), the assessment of R requires rainfall measurement by recording raingauges for 20–25 years. Lack of this type of measurement is a key problem in many African regions, where detailed rainfall data are often collected in a few gauged meteorological stations resulting in a scarce spatial coverage and the recording period is too short for calculating the mean annual value of the rainfall erosivity factor (Rutebuka et al. 2020).

As recording raingauge data are not easily available in many parts of the world, some rainfall indices calculated by using more readily available monthly and annual rainfall data were proposed.

Arnoldus (1980) proposed the following index, named Modified Fournier Index, MFI (mm), or also FAO index because FAO used it to establish erosion risk areas in North Africa and the Middle East (FAO 1967, 1977):

$$MFI = \sum_{i=1}^{12} \frac{p_{m,i}^2}{P} \quad (1)$$

in which $p_{m,i}$ (mm) is the mean rainfall depth in month i in a period of N years and P (mm) is the mean annual rainfall depth for the same period. Arnoldus (1980) suggested that MFI is a good approximation of R, to which it is linearly correlated.

In order to consider the actual monthly rainfall distribution during each year j of a period of N years, Ferro et al. (1991) and Aronica and Ferro (1997) introduced the annual value of the MFI index, $F_{a,j}$ (mm):

$$F_{a,j} = \sum_{i=1}^{12} \frac{p_{i,j}^2}{P_j} \quad (2)$$

where $p_{i,j}$ (mm) is the rainfall depth in month i of year j and P_j (mm) is the annual rainfall depth of year j. The main merit of this annual index is to preserve for each year the link between the monthly rainfall depths and the corresponding annual value. The mean annual value, F_F (mm), is calculated by the N annual values $F_{a,j}$ as follows:

$$F_F = \sum_{j=1}^{N} \frac{F_{a,j}}{N} \quad (3)$$

Both MFI and F_F have been largely used to derive estimating relationships of the rainfall factor of the USLE (Wischmeier and Smith 1978), R (MJ mm ha^{-1}h^{-1}yr^{-1}), usable when a limited information on rainfall is available.

In particular, using monthly rainfall from 132 raingauges in the continental United States, Renard and Freimund (1994) determined the following power relationship:

$$R = 0.7397\ MFI^{1.847} \quad (4)$$

Yu and Rosewell (1996), using rainfall data from 29 sites in southeastern Australia, proposed the following equation:

$$R = 3.827\ MFI^{1.41} \quad (5)$$

Ferro et al. (1991), in order to improve the methods for plotting the isoerosivity map for Sicily (Italy), established that the best result of the correlation analysis using non-recording raingauge data was a linear relationship between R and F_F. By a subsequent statistical analysis developed for 40 Sicilian raingauges, Ferro et al. (1999) determined that F_F is the best estimator of R factor and proposed the following equation:

$$R = 0.5249\ F_F^{1.59} \quad (6)$$

Vrieling et al. (2010) obtained an erosivity map for the African continent based on the application of the following relationship between R and MFI:

$$R = -1405 + 50.7\ MFI \quad (7)$$

For the Eastern African Region, Fenta et al. (2017) used the following relationship:

$$R = -189.2 + 27.8\ MFI \quad (8)$$

Recently, Rutebuka et al. (2020) proposed the following relationship by considering the (R, MFI) data pairs obtained for four stations in Rwanda:

$$R = -301 + 26.042\, MFI \quad (9)$$

Ferro et al. (1999) theoretically deduced the following equation:

$$MFI = \left[1 + CV^2\left(p_{m,i}\right)\right] \frac{P}{12} = K_m \frac{P}{12} \quad (10)$$

in which $CV(p_{m,i})$ is the coefficient of variation of the mean rainfall depths $p_{m,i}$ in the 12 months of the year and K_m is a constant. Equation (10) clearly demonstrates that the modified Fournier index is proportional to the mean annual rainfall, P.

Ferro et al. (1999) also deduced theoretically the following equation:

$$F_F = \left[\frac{\sum_{j=1}^{N} P_j \left[1 + CV^2\left(p_{i,j}\right)\right]}{\sum_{j=1}^{N} P_j} \right] \frac{P}{12} = K \frac{P}{12} \quad (11)$$

in which $CV(p_{i,j})$ is the coefficient of variation of the $p_{i,j}$ rainfall depth. For each raingauge, the constant K is an indicator of the monthly rainfall distribution in the year. A perfectly uniform distribution of the monthly rainfall depth in the year corresponds to $CV(p_{i,j}) = 0$ and $K = 1$, while K values more and more greater than unity correspond to more seasonal rainfall distribution.

USLE and RUSLE are generally used to predict average long-term soil loss values and to design soil conservation strategies finalised to limit soil loss to a tolerable value defined as "*the maximum level of soil erosion that will permit a high level of crop productivity to be sustained economically and indefinitely*" (Di Stefano and Ferro 2016; Carollo et al. 2013; Di Stefano et al. 2013). Considering that soil losses are frequently produced by a few severe rainstorms having high intensity and large rainfall depth (Larson et al. 1997), soil conservation strategies should be designed to protect land vulnerable to soil loss during severe rainfall events. This last choice imposes that the design of a soil conservation system should be carried out to limit soil loss to an acceptable value corresponding to rainfall depths having a chosen return period, T. If this procedure is applied, the theoretical probability distribution of the annual rainfall erosivity factor has to be assessed in order to estimate the rainfall erosivity factor, R_T, corresponding to a given return period.

In this paper, at first, using rainfall data from raingauges located at 13 sites in Burundi, the MFI and F_F erosivity indices are analysed to establish hydrological similitudes with other geographical regions. Then, in order to predict the erosion risk corresponding to a climatic condition of a given return period, the probability distribution of the annual value $F_{a,j}$ is studied. The descriptive ability of the Extreme Value Type 1 (EV1) distribution is investigated by an at-site and a regional procedure.

2 | Materials and Methods

Burundi is a small country located in East Africa, localised between 2°15′ and 4°30′ of latitude S and between 28°58′ and 30°53′ of longitude E (Figure 1). Burundi features a bimodal rainfall pattern that is driven by the progression of the Inter-Tropical Convergence Zone (ITCZ) (Nkunzimana et al. 2024). Two rainy seasons and two transition dry periods characterise the climate in Burundi. The first rainy season occurs between September and December (SOND) while the second rainy season covers March to May (MAM). A first dry short transition period, occurring in January and February, is known by the local name "*Umukubezi*" (JF) and a second longer dry period covers from June to August (JJA). The altitude ranges from 758 to 2675 m a.s.l.

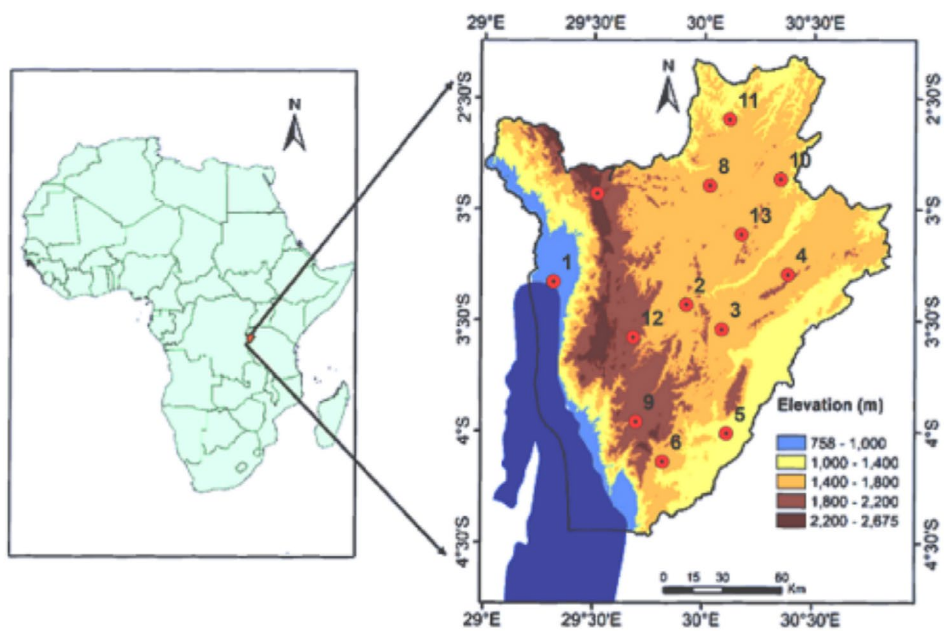

FIGURE 1 | Map of the considered Burundian raingauge stations.

TABLE 1 | Characteristic data of the investigated raingauges.

Rain-gauge	Elevation (m a.s.l.)	Period	N (years)	P (mm)	MFI (mm)	F_F (mm)	$\sigma(F_{a,j})$ (mm)
Bujumbura	783	1992–2022	31	764.8	89.4	107.6	24.2
Gitega	1660	1992–2022	30	1142.3	137.7	158.6	30.9
Muriza	1555	1975–2022	41	1132.6	140.2	162.2	33.5
Cankuzo	1535	1975–2022	38	1212.2	144.9	166.2	26.3
Musasa	1190	1975–2022	33	1126.8	132.4	153.4	27.7
Makamba	1453	1992–2022	31	1262.3	164.9	179.3	34.4
Rwegura	2258	1992–2022	31	1539.3	189.4	199.8	29.8
Nyamuswaga	1608	2000–2022	19	1287.4	146.8	164.5	28.6
Bururi-Vyanda	1848	1993–2022	29	1434.3	187.7	204.0	27.9
Muyinga	1626	1992–2022	31	1094.7	138.0	145.7	25.6
Kirundo	1436	2000–2022	21	1059.4	116.6	135.2	13.3
Gisozi	2091	2000–2022	21	1533.5	172.8	198.5	46.5
Karuzi	1599	2000–2022	22	1222.7	144.1	167.8	41.4

Note: N = years of observation; P = mean annual rainfall depth; MFI = Modified Fournier Index; F_F = erosivity index by Ferro et al. (1991); $\sigma(F_{a,j})$ = standard deviation of the annual values of the erosivity index by Ferro et al. (1991).

The data used in this research are the Burundian monthly and annual rainfalls recorded by the Geographic Institute of Burundi in the period 1975–2022 with different periods, that in some cases are temporally discontinuous, for the 13 analysed raingauges. In Table 1, for each investigated raingauge, the elevation, the sampling period, and the sample size, N (years), are listed. For the 13 sites, the values of P, MFI, F_F and the standard deviation $\sigma(F_{a,j})$ are also listed in Table 1.

The knowledge of F_F may allow for long term average soil loss predictions for an area of interest but it does not by itself allow one to predict the erosion risk associated with a rainfall forcing of a given return period (Aronica and Ferro 1997; Ferro et al. 1999). Starting from this premise, Ferro et al. (1991) suggested that a site should be characterised by an erosion risk index, defined as the ratio between the $F_{a,T}$ quantile corresponding to an average recurrence interval of T years and the mean annual value, F_F. A T value of 50 years was considered appropriate to calculate this erosion risk index (Ferro et al. 1991, 1999; Aronica and Ferro 1997).

The estimate of the $F_{a,T}$ quantile requires to assess the theoretical distribution function which agrees with the empirical cumulative distribution function, CDF, of each sample of the annual erosivity index $F_{a,j}$. Considering that the Burundian sampled sites have a limited size ($21 \leq N \leq 41$ years), for limiting the consequent uncertainty of the at-site estimates of the quantiles $F_{a,T}$, a probability distribution with two parameters was selected. In particular, following Aronica and Ferro (1997) and Ferro et al. (1999), an at-site procedure was applied to test the suitability of the EV1 distribution as the parent distribution for the 13 investigated Burundian samples.

For testing the EV1 distribution as regional parent distribution for Burundi, the at-site analysis was developed by using Gumbel's probabilistic diagram and the skewness test (Matalas et al. 1975).

Gumbel's diagram is a plot that allows for representing the pairs ($F_{a,j}$, y), where y is the Gumbel's normalised variable corresponding to the original variable $F_{a,j}$ that has to be calculated by the following relationship (Gumbel 1958):

$$y = -\ln\left[ln\left(\frac{1}{\mathrm{P}(F_{a,j})}\right)\right] \tag{12}$$

in which $\mathrm{P}(F_{a,j})$ is the empirical cumulative frequency of each value $F_{a,j}$ of a given sample having a size N. If an empirical sample of the variable $F_{a,j}$ is distributed according to the theoretical EV1 distribution (Santner 1973), the following linear relationship between y and $F_{a,j}$ must be positively verified:

$$y = \alpha\left(F_{a,j} - u\right) \tag{13}$$

in which α and u are the two parameters of the EV1 distribution which are estimated using the method of the moments by the following relationships:

$$\alpha = \frac{1.283}{\sigma\left(F_{a,j}\right)} \tag{14}$$

$$u = F_F - \frac{0.5772}{\alpha} \tag{15}$$

The test is positively verified if the N empirical pairs ($F_{a,j}$, y) plotted on Gumbel's diagram are near the straight line having equation (13).

For each raingauge, the skewness test (Matalas et al. 1975) is based on the comparison between sample skewness coefficient of $F_{a,j}$, G, with the expected theoretical skewness, $E(\gamma)$, which depends on the sample size N. The statistical hypothesis is accepted at a probability level equal to 95% if the absolute value of the difference between G and $E(\gamma)$ is less than twice the expected standard deviation of the skewness coefficient, $\sigma(\gamma)$. In this approach, both $E(\gamma)$ and $\sigma(\gamma)$ are calculated as a function of the sample size N according to the following relationships (Aronica and Ferro 1997) obtained by the data of Matalas et al. (1975):

$$E(\gamma) = 0.2995\, N^{0.2841} \tag{16}$$

$$\sigma(\gamma) = 0.9474\, N^{-0.165} \tag{17}$$

3 | Results and Discussion

3.1 | Analysis of MFI and F_F

The *MFI* and F_F values for the considered Burundian stations (Table 1) were used to (i) evaluate rainfall erosivity in Burundi according to some literature suggestions; (ii) verify applicability of Equations (10) and (11); (iii) test the effect of the data analysis method on determination of regional K_m (*MFI*) and K (F_F) values; (iv) compare *MFI* with F_F; (v) compare a simplified method to predict *MFI* in Rwanda with a similar method derived in this investigation for Burundi; and (vi) establish comparisons between the Burundian K_m and K values with the corresponding values obtained in other parts of the world.

Overall, these analyses considered some aspects that have been little developed in scientific literature, such as the link between *MFI* and F_F, and placed Burundian data in a wider geographical context.

Based on CEC (1994), the *MFI* erosivity ranges and corresponding qualitative descriptions are: very low ($MFI < 60$ mm), low ($MFI = 60$–90 mm), moderate ($MFI = 90$–120 mm), high ($MFI = 120$–160 mm) and very high ($MFI > 160$ mm) (Fenta et al. 2017). On average, *MFI* was equal to 146.5 mm ($\sigma(MFI) = 27.6$ mm) in Burundi, according to the data collected at the 13 considered stations (Table 1). An *MFI* value greater than 120 mm was obtained for 85% of the considered Burundian stations, and $MFI > 160$ mm was obtained in 31% of the cases. Therefore, according to this classification, rainfall erosivity is generally high and occasionally very high in Burundi.

If the regional values of K_m and K are known, Equations (10) and (11) have also a practical attractiveness since they suggest that knowledge of mean annual rainfall is enough to calculate both *MFI* and F_F. In other terms, with these two equations, the knowledge of monthly rainfall values as the mean of a multi-year period (*MFI*) or for each year of the multi-year period (F_F) becomes unnecessary. However, the applicability of equations (10) and (11) has not been widely verified in areas other than Italy and Australia (Ferro et al. 1999). Moreover, empirical linear relationships between *MFI* and *P* that include an intercept differing from zero have been reported, also for regions close to Burundi (Bagarello 1996; Muhire et al. 2015).

Equations (10) and (11) were tested for the Burundian stations. For both erosivity indices, Figure 2 suggested that the linear regression line obtained by fixing the intercept at zero practically overlapped with the one obtained without any constraint on the intercept and hence the coefficient of determination, R^2, did not vary if not marginally (*MFI*: $0.910 \le R^2 \le 0.912$; F_F: $0.930 \le R^2 \le 0.936$). Moreover, the 95% confidence intervals for the intercept of the *MFI* versus $P/12$ and F_F versus $P/12$ relationships included zero in both cases since they were equal to −38.8—25.2 in the former case and to −14.7—39.0 in the latter one.

Therefore, this analysis confirmed the applicability of Equations (10) and (11). In other terms, both *MFI* and F_F are directly proportional to the mean annual rainfall depth, as theoretically expected (Ferro et al. 1999).

With reference to the 13 considered stations, the mean annual rainfall depth, *P*, can be expected to increase with elevation, *el* (m a.s.l.) (Figure 3a). An implication of this finding is that an approximate estimate of both *MFI* and F_F can be obtained if only the elevation of the point of interest is known (Figure 3b).

According to Ferro et al. (1999), the K_m and K values for a region of interest can be obtained by linear regression analysis of all available erosivity index (*MFI*, F_F) versus $P/12$ data points but also by calculating K_m ($=12 \times MFI/P$) or K ($=12 \times F_F/P$) for each station and then averaging the individual values of the constant.

The Burundian K_m value was equal to 1.45 using linear regression analysis procedures (Figure 2a) and to 1.44 by considering the mean of the 13 individual K_m values (standard deviation, $\sigma(K_m) = 0.077$). The K value was equal to 1.62 in the former case (Figure 2b) and to 1.63 ($\sigma(K) = 0.068$) in the latter one. Therefore, the applied data analysis procedure did not have any effect on the Burundian values of K_m and K.

Both *MFI* and F_F have been used to estimate the rainfall factor, *R*, of the USLE (Wischmeier and Smith 1978). For example, an *R* vs. *MFI* relationship was deduced by Rutebuka et al. (2020) by considering four rain-gauge stations in Rwanda whereas Ferro et al. (1999) estimated *R* in Sicily (Italy) as a function of F_F. The F_F index was introduced as an alternative to the *MFI* index to take into account the actual monthly rainfall distribution during each year *j* of a period of *N* years (Aronica and Ferro 1997; Ferro et al. 1999). An obvious key to understanding this statement is that *MFI* and F_F should not be expected to coincide with each other. The link between *MFI* and F_F, that has received little attention so far, was investigated for the considered Burundian stations.

The two indices were strongly correlated ($R^2 = 0.97$) but the linear regression line between F_F and *MFI* did not coincide with the identity line (Figure 4). In particular, the 95% confidence interval for the slope was equal to 0.84–1.09, and hence included unity, but that for the intercept was of 5.3–41.4 and hence it did not include zero. Therefore, F_F and *MFI* differed from each other. Another analysis was carried out by considering the fitted Equations (10) and (11) to the Burundian data:

$$\frac{F_F}{MFI} = \frac{1.623 \times (P/12)}{1.447 \times (P/12)} = 1.12 \tag{18}$$

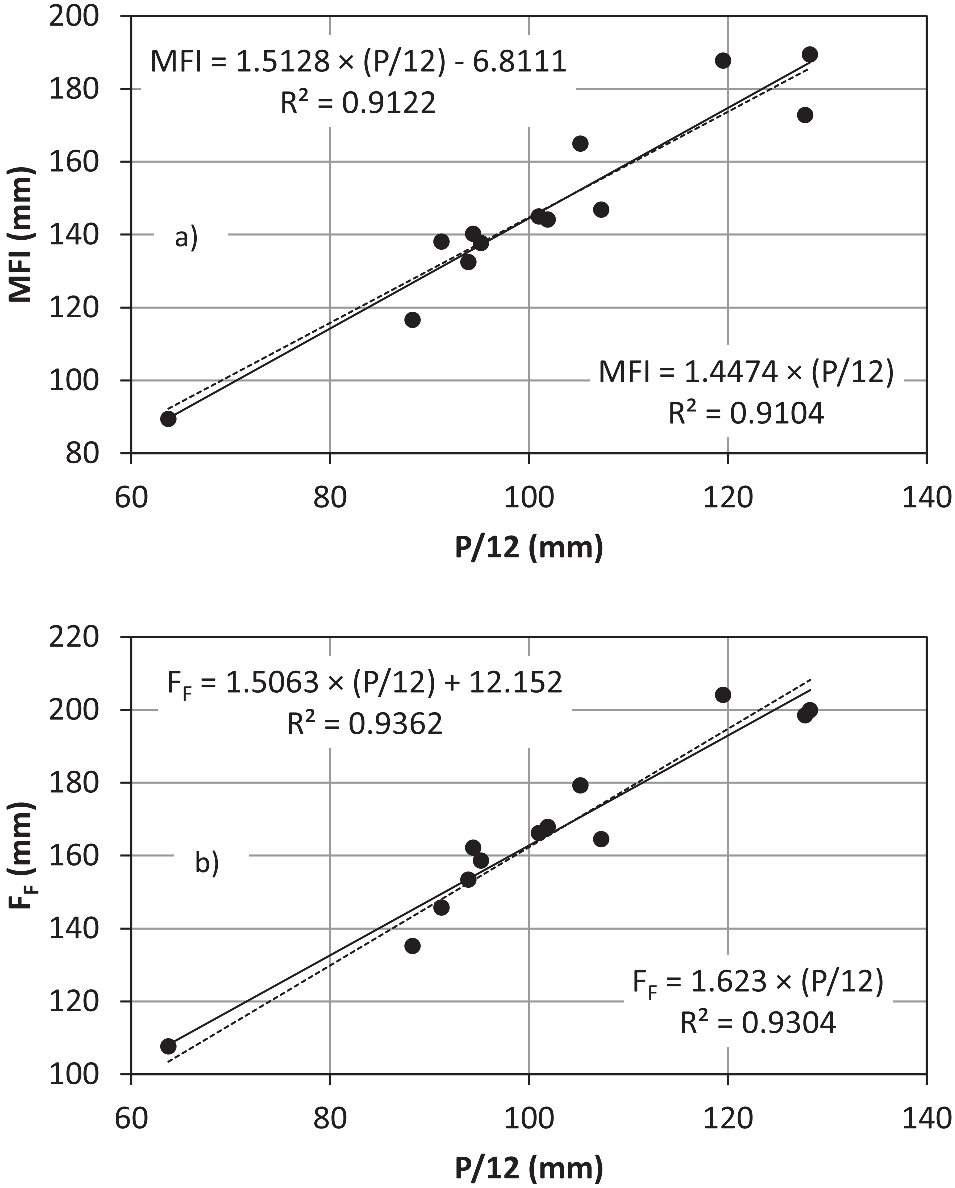

FIGURE 2 | Relationship between (a) the Modified Fournier Index, *MFI*, and (b) the erosivity index by Ferro et al. (1999), F_F, and one twelfth of the mean annual rainfall depth, *P*.

Therefore, the two erosivity indices are expected not to coincide and to differ by 1.12 times (Figure 4).

The ratio K/K_m, which is equal to 1.12 for Burundi, was also calculated for the regions investigated by Ferro et al. (1999) and it ranged from 1.36 for South Australia to 1.50 for Apulia. As a consequence, among the tested regions, Burundi is characterised by the maximum similarity between the two climatic indices.

Consequently, adapting the rainfall erosivity classification by CEC (1994) to the Burundian F_F values, very low, low, moderate, high and very high erosivity levels are associated with $F_F \leq 67$ mm, $67 < F_F \leq 101$ mm, $101 < F_F \leq 134$ mm, $134 < F_F \leq 179$ mm and $F_F > 179$ mm, respectively.

For Rwanda, bordering Burundi, Muhire et al. (2015) obtained the following relationship between *MFI* and *P*, valid for $740 \leq P \leq 1550$ mm:

$$MFI = 50.139 + 0.0797P \tag{19}$$

A very similar range of *P* values was obtained in Burundi in this investigation since *P* varied from a minimum of 765 mm at Bujumbura to a maximum of 1539 mm at Rwegura (Table 1). For the Burundian stations, Equation (10) can be written as:

$$MFI = 0.1206\, P \tag{20}$$

The comparison between Equations (19) and (20) (Figure 5) shows that the Rwandan relationship predicts higher *MFI* values than the Burundian one for relatively small *P* values while the opposite occurs for the highest *P* values. Differences between the two relationships vary from +22% for $P = 750$ mm to −7% for $P = 1550$ mm. Therefore, the two relationships are not equivalent but, in the range of the higher values of *P*, they appeared to provide rather similar predictions of *MFI*.

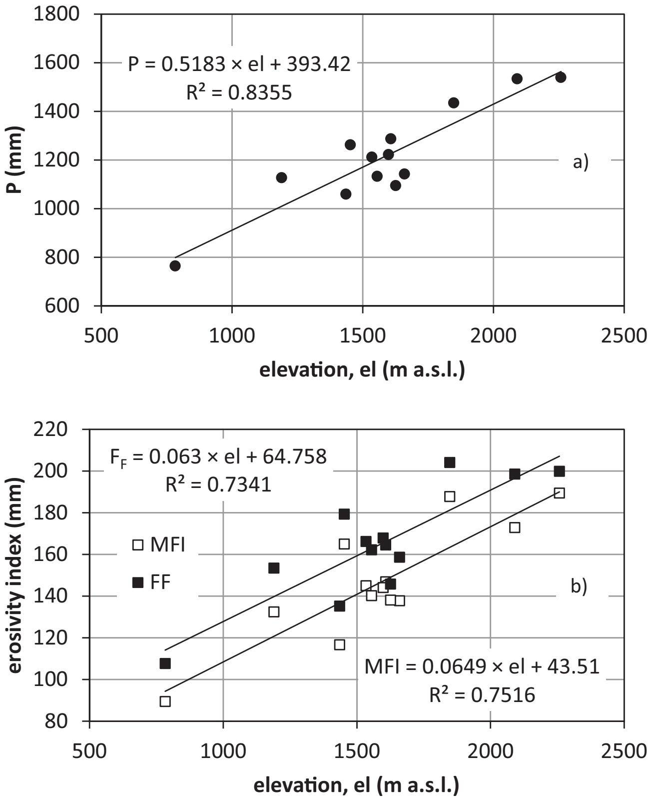

FIGURE 3 | Relationships between (a) the mean annual rainfall depth, *P*, and the elevation of the raingauge station, *el*, and (b) the considered erosivity indices (*MFI* = Modified Fournier Index; F_F = erosivity index by Ferro et al. 1999) and *el*.

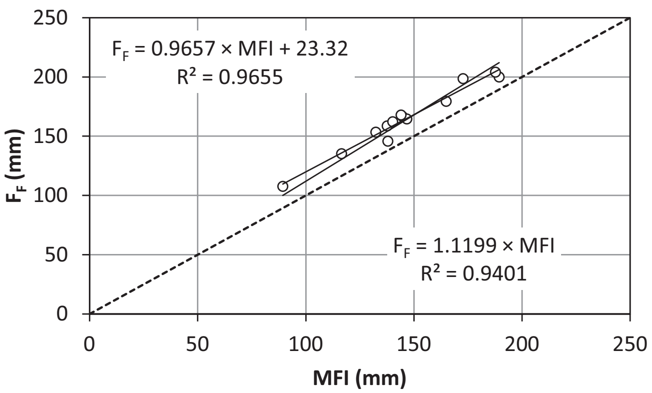

FIGURE 4 | Relationship between the erosivity index by Ferro et al. (1999), F_F, and the Modified Fournier Index, *MFI*.

Figure 6 compares the Burundian value of K_m with those obtained by Ferro et al. (1999) in other regions of the world. The Burundian value is the highest among all the reported values, but it is very close to the K_m values obtained in Portugal and Sicily. Therefore, according to Ferro et al. (1999), rainfall distribution in the year is not uniform in Burundi.

Ferro et al. (1999) also listed the means of *K*, *m*(*K*), and the associated $\sigma(K)$ values for different Australian and Italian regions and they suggested that the relationship between these two statistical parameters can be considered unique.

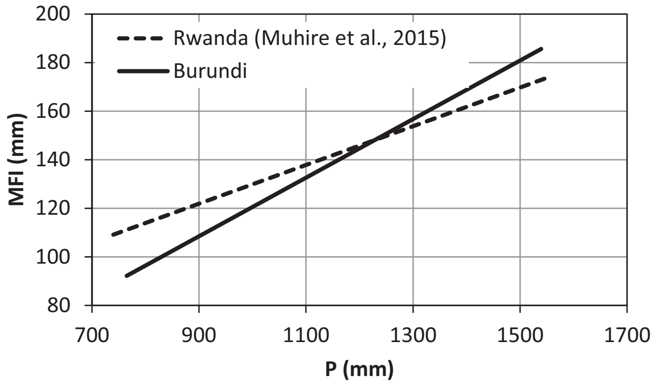

FIGURE 5 | Relationships between the Modified Fournier Index, *MFI*, and the mean annual rainfall depth, *P*.

The uniqueness of the relationship between σ (*K*) and *m*(*K*) was confirmed by also considering the Burundian data point (Figure 7).

3.2 | At-Site Analysis of the Probability Distribution of $F_{a,j}$ Index

For each investigated raingauge, Table 2 lists the sample coefficient of variation, *CV*, and skewness, *G*, of $F_{a,j}$, the parameters α and *u* estimated by the method of the moments, and the results of the Gumbel's probabilistic diagram (GPD) and the skewness test (ST), expressed as "yes" if the hypothesis that the sample is distributed as an EV1 was accepted and "no" for the opposite case.

For four raingauges characterised by high sample sizes (Muriza, Cankuzo, Musasa and Makamba), Figure 8 shows the result of the test by the Gumbel's diagram. For the four raingauges shown in Figure 8, Table 2 demonstrates that the skewness test accept the hypothesis that the sample is distributed according to an EV1. Table 2 also shows that, for three raingauges (Bururi-Vyanda, Kirundo and Gisozi), the hypothesis that the sample is distributed according to an EV1 cannot be accepted. This last result can perhaps be justified considering that this case corresponds to samples having, at least in two cases, small sample sizes *N*.

In conclusion, the analysis of Table 2 allows us to assess that the $F_{a,j}$ variable can be generally assumed to be distributed according to the EV1 distribution, as two of the three detected exceptions to this hypothesis correspond to raingauges with small sample sizes.

3.3 | Regional Analysis of the Probability Distribution of $F_{a,j}$ Index

For validating the hypothesis that the EV1 distribution can be applied as a regional parent distribution (Cannarozzo et al. 1995) and to reduce the uncertainty of the quantile estimate of given return period $F_{a,T}$, which is particularly high when *T* is much greater than the sample size *N*, the analysis was developed using contemporaneously rainfall data of all

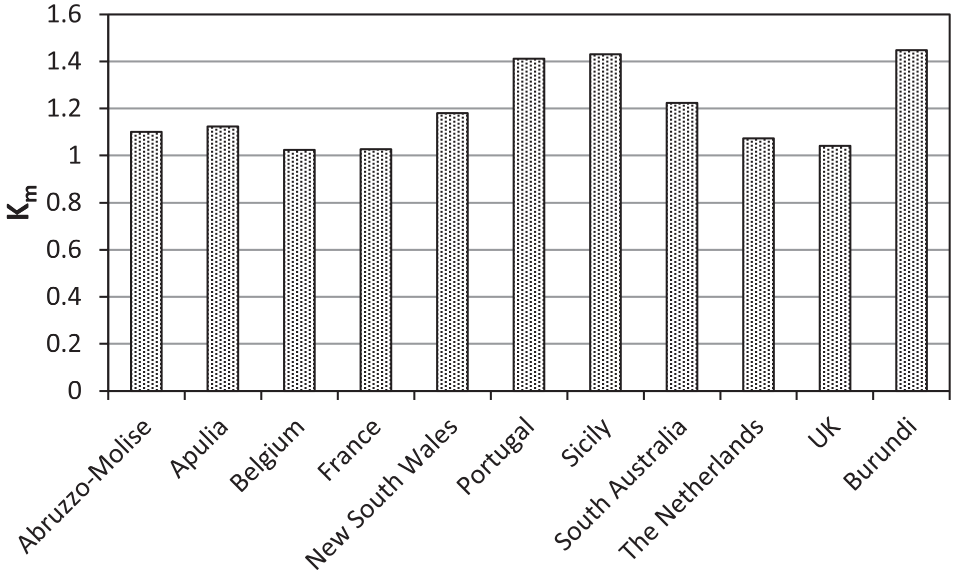

FIGURE 6 | Comparison between the Burundian value of the K_m constant of Equation (10) and the corresponding values obtained by Ferro et al. (1999) in other regions of the world.

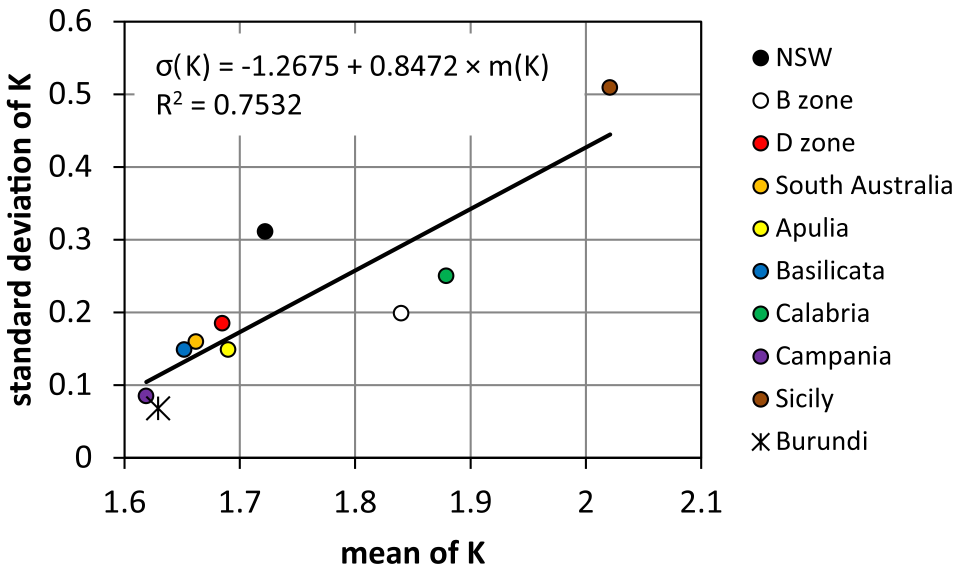

FIGURE 7 | Relationship between the standard deviation, $\sigma(K)$, and the mean, $m(K)$, of the K constant of Equation (11) obtained by considering, in addition to the data by Ferro et al. (1999), the Burundian data point.

13 raingauges. In particular, the sample annual $F_{a,j}$ values of each raingauge were made dimensionless by dividing each annual value by the corresponding mean annual value, F_F. Figure 9 shows the cumulative empirical frequency distributions of $F_{a,j}/F_F$ for the 13 Burundian raingauges. This figure demonstrates that these distributions can be considered overlaid and, according to this result, a single regional distribution of $F_{a,j}/F_F$ can be obtained considering a single sample constituted of 378 data points (Figure 10).

The empirical cumulative frequency distribution of $F_{a,j}/F_F$ was also plotted on the Gumbel's probabilistic diagram (Figure 11) and this test was positively verified as the 378 empirical pairs ($F_{a,j}/F_F$, y) plotted on the Gumbel's diagram were near the straight line having equation (13) with $\alpha = 6.9462$ and $u = 0.9219$:

$$y = 6.9462\left(\frac{F_{a,j}}{F_F} - 0.9219\right) \tag{21}$$

Using the relationship between non-exceedance probability $P(F_{a,j}/F_F)$ and return period, Equation (12) can be rewritten as follows:

$$y = -ln\left[ln\left(\frac{T}{T-1}\right)\right] \tag{22}$$

Combining Equations (21) and (22) the following equation is obtained:

$$\frac{F_{a,T}}{F_F} = y_T = 0.9219 - 0.1440\, ln\left[ln\left(\frac{T}{T-1}\right)\right] \tag{23}$$

TABLE 2 | Statistical parameters of the investigated raingauges.

Rain-gauge	*N* (years)	*CV*	*G*	*α*	*u*	GPD	ST
Bujumbura	31	0.225	0.454	0.0530	96.7	Yes	Yes
Gitega	30	0.183	0.596	0.0451	142.9	Yes	Yes
Muriza	41	0.207	0.545	0.0382	147.1	Yes	Yes
Cankuzo	38	0.158	−0.145	0.0488	154.4	Yes	Yes
Musasa	33	0.181	−0.102	0.0463	140.9	Yes	Yes
Makamba	31	0.192	0.273	0.0373	163.8	Yes	Yes
Rwegura	31	0.149	0.783	0.0431	186.4	Yes	Yes
Nyamuswaga	19	0.174	0.322	0.0448	151.6	Yes	Yes
Bururi-Vyanda	29	0.137	−0.330	0.0460	191.5	Yes	No
Muyinga	31	0.176	1.462	0.0501	134.2	Yes	Yes
Kirundo	21	0.099	−1.564	0.0961	129.2	No	No
Gisozi	21	0.234	1.916	0.0276	177.6	No	No
Karuzi	22	0.247	1.085	0.0310	149.2	Yes	Yes

Note: N = years of observation; CV = coefficient of variation of the annual values of the erosivity index by Ferro et al. (1991); G = skewness of the annual values of the erosivity index by Ferro et al. (1991); α and u = parameters of the EV1 distribution; GPD = result of the Gumbel probabilistic diagram; ST = result of the skewness test. GPD and ST columns: "Yes" denotes that the hypothesis that the sample is distributed as an EV1 was accepted; "No" indicates that the hypothesis was not accepted.

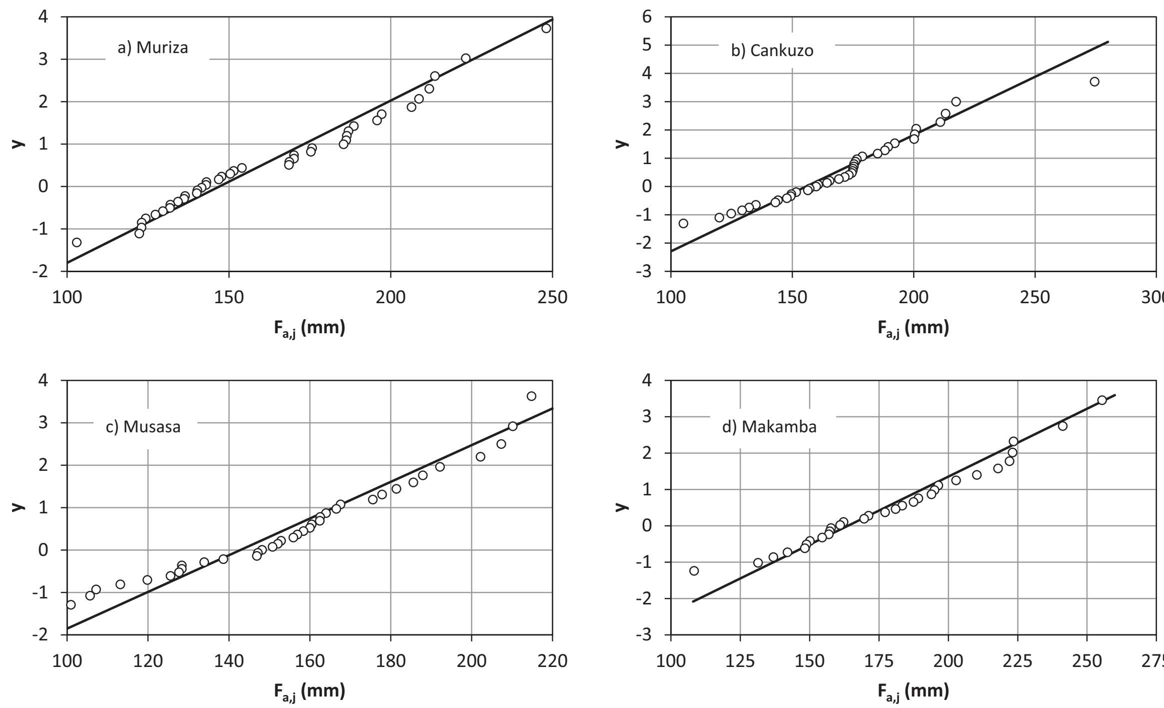

FIGURE 8 | Gumbel's diagram for the (a) Muriza, (b) Cankuzo, (c) Musasa and (d) Makamba rain-gauge stations.

in which y_T is the frequency factor depending on the regional EV1 parameters and the return period T.

For Burundi, Equation (23) establishes that the value of $F_{a,j}$ corresponding to a given return period, $F_{a,T}$, can be obtained by amplifying the mean value F_F by a frequency factor equal to the second member of Equation (23). In particular, for $T = 50$ years, the frequency factor is equal to 1.48.

Using the data by Rutebuka et al. (2020), the following relationship was obtained:

$$R = 23.85\ MFI \tag{24}$$

which is characterised by a coefficient of determination of 0.9562. Equation (24) was used to estimate R for the 13 Burundian rain-gauges, using the calculated MFI values (Table 1). Then, these

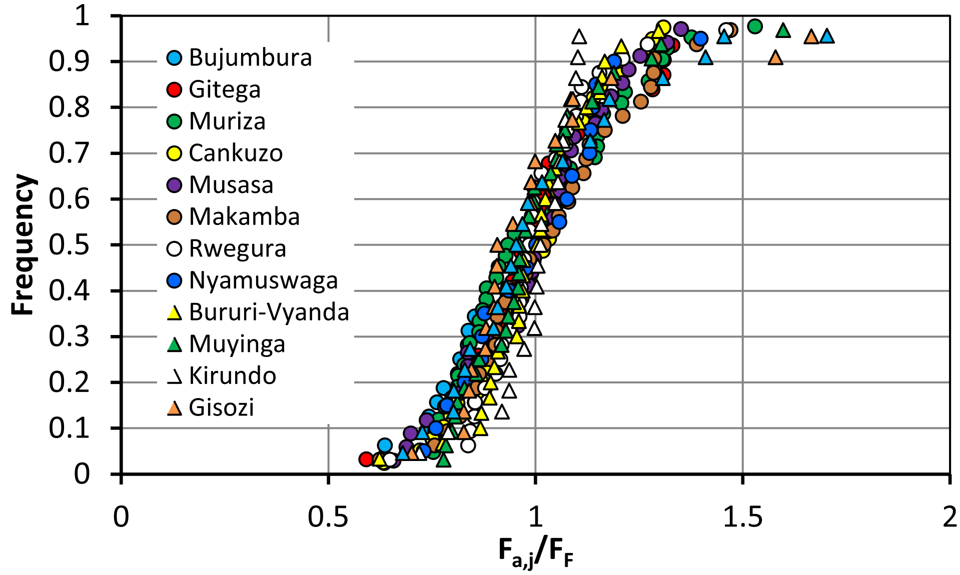

FIGURE 9 | Cumulative empirical frequency distributions of $F_{a,j}/F_F$ for the 13 Burundian raingauge stations.

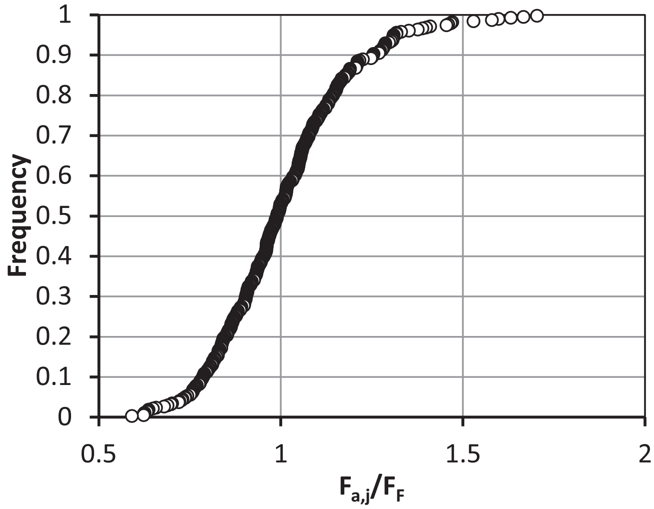

FIGURE 10 | Regional distribution of $F_{a,j}/F_F$ obtained by considering a total of 13 Burundian raingauge stations and 378 individual data points.

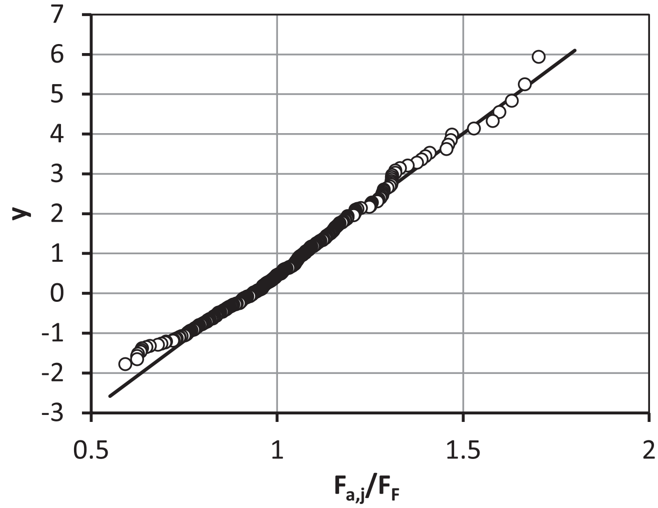

FIGURE 11 | Plot of the 378 empirical pairs ($F_{a,j}/F_F$, y) on the Gumbel diagram.

estimates of R were plotted against the calculated values of F_F (Table 1) to obtain the following relationship (Figure 12):

$$R = 21.27\, F_F \tag{25}$$

which is characterised by a coefficient of determination of 0.9539. According to Equation (25), considering that the mean annual value of the rainfall erosivity factor R is proportional to F_F, the following relationship holds:

$$\frac{R_T}{R} = \frac{F_{a,T}}{F_F} \tag{26}$$

In conclusion, Equation (26) demonstrates that the frequency factor y_T can be applied to estimate both the quantiles of the USLE rainfall erosivity factor and $F_{a,j}$. In other words, the same frequency factor can be applied to amplify R and F_F.

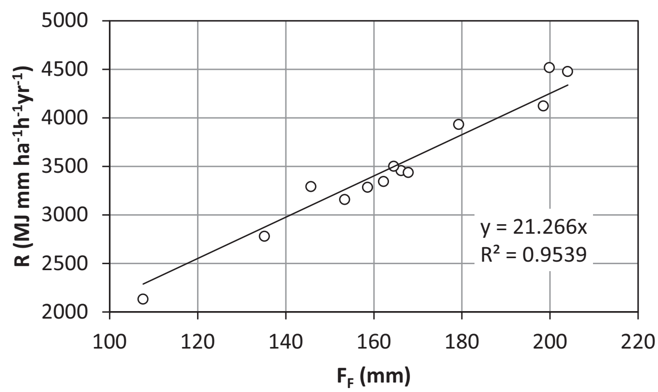

FIGURE 12 | Relationship between the R-factor estimated according to Rutebuka et al. (2020) by the Modified Fournier Index, *MFI*, and the erosivity index by Ferro et al. (1999), F_F, for the 13 considered Burundian raingauge stations.

4 | Conclusions

Soil erosion by water is a major threat to soil that is considered a non-renewable resource as the formation of new soil is very slow process when normal agricultural conditions occur, while its degradation due to erosion phenomena is rapid and is frequently accelerated by human activities. The USLE and its revised version are widely applied as they continue to be a good compromise between input data required for their application and reliability of soil loss estimates. Furthermore, the rainfall erosivity factor R of the USLE is a useful tool to identify areas with a high soil loss risk, in which soil conservation practises or strategies should be assessed.

At first, the theoretical relationships between MFI and the mean annual rainfall P and between F_F and P were tested by the monthly rainfall depth data available for thirteen Burundian raingauges. The constants K_m and K, linking MFI and F_F with P, were also used to assess hydrological similitude with other geographical regions. The developed analysis demonstrated that the applied estimate procedure (linear regression or mean of the 13 values) does not affect the estimate of K_m (1.44–1.45) and K (1.62–1.63). The comparison with previous results by Ferro et al. (1999) confirmed that the mean values of K_m and K are dependent on geographical factors, and it also supported the applicability of the relationship between $\sigma(K)$ and $m(K)$ determined by Ferro et al. (1999) with the Burundian data point.

In order to predict the erosion risk corresponding to a climatic condition of given return period, the applicability of the Extreme Value Type 1 (EV1) probability law to the annual values $F_{a,j}$ was tested by an at-site analysis and a regional procedure. The at-site analysis assessed the applicability of the EV1 as the parent distribution of the variable $F_{a,j}$, while the regional procedure allowed us to conclude that the EV1 can be applied as the parent distribution of the variable $F_{a,j}/F_F$. According to this last result, the quantile corresponding to a given return period, $F_{a,T}$, can be obtained by amplifying the mean value F_F by a frequency factor equal to the second member of Equation (23).

In conclusion, considering that the mean annual value of the rainfall erosivity factor R is proportional to F_F, the quantile R_T can be estimated amplifying the mean value R by the frequency factor calculated by Equation (23) which holds for the whole Burundian region.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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