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Water Erosion Factors Modeling in the N'Zérékoré City, Republic of Guinea

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Abstract: Soil erosion from water has become a relevant issue at global level. In Guinea in particular, erosion has worrying effects, due to natural conditions and human impact, especially in the Nzérékore city in forest region. This paper proposed a soil erosion modeling by rainfall effect in the prefecture of N'Zérékoré. To achieve this objective, monthly and annual rainfall data for the N'Zérékoré city were collected at the meteorological station over the period from 1980 to 2024. The analysis of rainfall aggressiveness was possible using the Fournier index. For data processing, we used Microsoft Excel, Python and the ARIMA (AutoRegressive Integrated Moving Average) model for soil aggressiveness predicted by rainfall. It was found that, from 2000 to 2009, erosion was higher compared to other periods with a rate of 60%, or 6 years of high rainfall aggression. From the periods 1990 to 1999 and 2010 to 2019, the lowest rainfall aggressiveness was recorded, with 60% or 6 years of low erosivity. However, from period 1980 to 1989 the highest rate (70%) of very high rainfall erosivity was recorded. The results show three levels of rainfall aggressiveness on an annual scale: a very high level of erosivity with a rate of 22.2% or 10 years, followed by a high level of 35.6% or 16 years of strong erosion. The moderate erosivity level corresponds to 42.2% or 19 years. The model predicts a stability of the erosivity index around 77.14 over the period 2025-2034. During the forty (45) years the rainfall erosivity index was very unstable characterized by strong erosion, however it would be stable in the next ten (10) years.

Key words: Rainfall factor, water erosion, erosivity index, N'Zérékoré.

1. Introduction

The erosion phenomenon dates back millions of years. Therefore, all developing civilizations have faced this phenomenon and have tried to find solutions with varying results, developing anti-erosion techniques adjusted to ecological and socio-economic conditions [1]. Water erosion (soil erosion caused by runoff water) is caused by raindrops which causes the decomposition of soil aggregates, followed by the movement of particles loose by runoff [2]. It is determined by the physical characteristics of the material, the volume and speed of water, as well as the slope. Erosion occurs quite easily, as the components of a soil are not uniform [3]. Erosion is a common process and represents a global environmental issue, which hinders sustainable progress [4, 5].

Indeed, water erosion is a complex and interdependent process. Determining factors include abrupt spatio-temporal variations in climatic parameters (precipitation, temperature, etc.), runoff [6], as well as topography, soil texture, vegetation, cultivation methods, and potential human actions. These elements are all amplified by human activity [7]. Climatic, soil, and topographic characteristics determine runoff and erosion risks on cultivated land. Nevertheless, the main elements of soil erosion can be classified into three categories:

(1) energetic factors (rainfall intensity, runoff water quantity, wind power, local slope, hill slope, and length);

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(2) protective factors (vegetation, aesthetic appeal or pressure for employment and land management);

(3) resistance factors (soil erosion capacity, infiltration potential and soil management) [8].

In the N'zi-Comoé region in Ivory coast, precipitation indices not enough analyzed reveal a multifactorial vulnerability to water erosion of 37% [9]. In Benin, rainfall is intense and reaching an average of 4,000 mm per year, or 90% of the year. They are characterized by significant runoff which impacts agricultural land [10].

The Guinean population faces a variety of challenges including food insecurity and poor agricultural land. Heavy rainfall, which can reach up to 3,000 mm per year, and the loss of vegetation cover in Guinean forests both contribute to the degradation of soil fertility [11]. Agricultural yields are affected by land degradation due to water erosion in this region.

This situation is of concern not only to the population, decision-makers at both national and international levels, but also to researchers. Indeed, without economic growth supported by relevant research, poverty will not disappear and food insecurity will persist in the Republic of Guinea.

Rainfall intensity plays a crucial role among the natural factors that influence soil erosion. Constituent particles can be dispersed and aggregates broken down by the impact of raindrops. These particles appear on the soil surface when the erosion force exceeds the soil's separation resistance. A precise understanding of the erosion potential of rainfall can be beneficial for implementing anti-erosion measures and slowing the spread of agricultural soil degradation. In this context, rainfall intensity is the main key element of erosion. The study of rainfall erosivity helps guide and anticipate soil erosion potential.

2. Materials and Methods

2.1 Materials

2.1.1 Study Area

The N'Zérékoré city is one of the 33 cities of Guinea. It is the largest city in the Forest Guinea region in the south-east of the Republic of Guinea. The city is also the capital of the N'Zérékoré region and located between 7°32′ and 8°22′ North latitude and 9°04′ West longitude. Its area is 47.3 km^2. The distance to neighboring cities is 39 km for N'Zérékoré-Lola, 62 km for N'Zérékoré-Yomou, 125 km for N'Zérékoré-Beyla, and 135 km for N'Zérékoré-Macenta. Nzérékoré city is at an elevation of 480 m and its relief is rugged. The plateau is dominated by hills that are sometimes gneissic (Gonia) and sometimes quartz (Gboyéba). The city has three important mountains: Götö (450 m), Hononye (350 m) and Kwéléyé (350 m) [12]. Fig. 1 gives the map of the Nzerekore City.

2.1.2 Data Collection

The assessment of the soil aggressiveness by water in N'Zérékoré city is based on monthly rainfall data from 1980 to 2024, which come from the city's meteorological station on a period of 45 years.

2.2 Methods

2.2.1 Rainfall Erosivity Estimation on an Interannual Scale

The annual rainfall erosivity (R) is used to assess the erosive capacity of rainfall in a region. In our study, we used the rainfall data available at the N'Zérékoré meteorological station. To determine the interannual rainfall erosivity, the rainfall aggressiveness index is calculated using the following formula [13]:

$$\mathrm{IAP} = (X_i - \bar{X})/\sigma$$

where, X_i represents the rainfall of year i;

$\bar{X}$ and σ are respectively the mean and standard deviation of the average interannual rainfall over the reference period;

IAP, the Rainfall Aggression Index

For the classification of interannual rain aggressiveness, we used the below table (Table 1).

2.2.2 Estimation of Rainfall Erosivity on an Annual Scale

To better assess the aggressiveness of the local climate, particularly rainfall, the Fournier climate aggressiveness index was used, which appeared to be well suited to the

West African climate. This index takes into account the rainfall of the wettest months and the average annual rainfall [14]. Its expression is as follows:

$$R=p^2/P$$

where R represents erosivity index; p, average precipitation of the wettest month; and P average annual precipitation.

To better assess the index values, Atherton et al. [15] and Paul-Hus [16] defined the following classes:

- $R < 70$ mm, indicates, the erosive capacity of the rain is moderate;
- R between 70 and 100 mm, indicates the erosive capacity of the rain is high;
- $R > 100$ mm indicates very high erosive capacity of the rain.

Fournier's climate aggressiveness index allows us to assess the erosive capacity of the climate [17]. For data processing, we used Microsoft Excel and Python software. Then, the ARIMA (AutoRegressive Integrated Moving Average) model was used to project the aggressiveness of rainfall in the future.

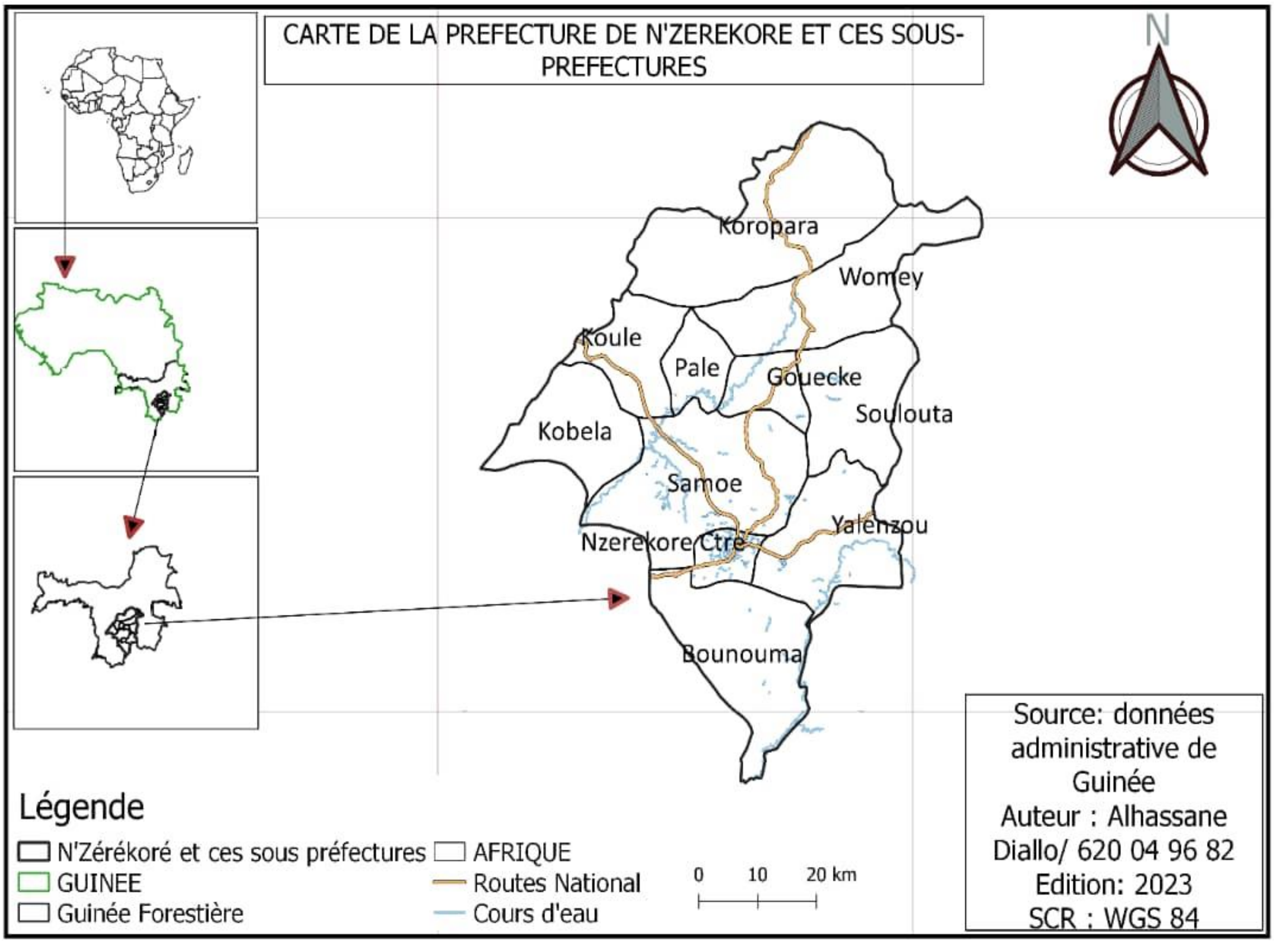

Fig. 1 Map of the Nzérekore city.

Table 1 Classification of rainfall aggressiveness on an interannual scale.

Rainfall regimes	IAP classes	Degree of rainfall aggressiveness
Very humid	IAP > 1.49	Very strong
Humid	1 < IAP ≤ 1.49	Strong
Normal	IAP = 0	Average
Dry	-1.49 ≤ IAP < -1	Weak
Very dry	IAP < -1.49	Very weak

Source: Commission of European Communities, 1992.

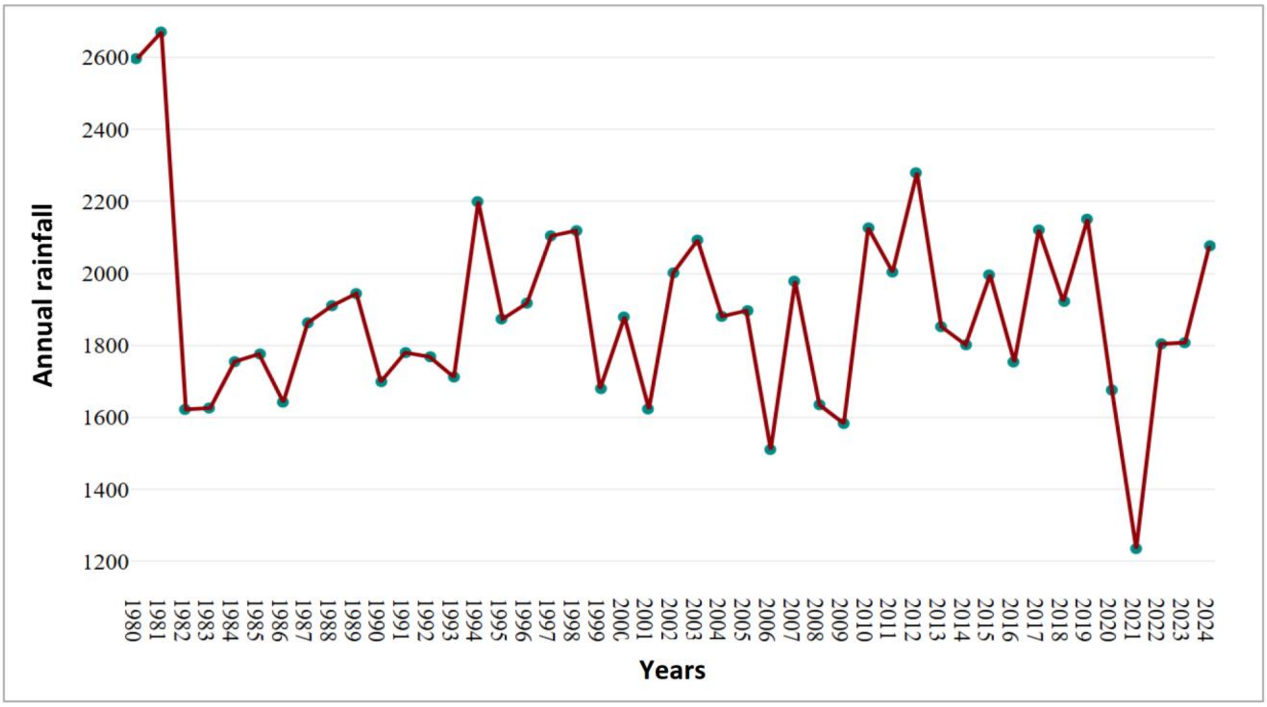

Fig. 2 Height of annual rainfall in the prefecture of N'Zérékoré (1980-2024).

3. Results and Discussions

Fig. 2 illustrates the height of the annual rainfall in the city of N'Zérékoré during the period of 1980-2024. It shows the global evolution of the height of annual rainfall for 45 years in the N'Zérékoré city and allows us to understand that the amount of rainfall is higher in 1981 with 2,670.39 (mm). In this period 1980-2024, thirteen (13) years have a deficit rainfall: 1982, 1983, 1984, 1986, 1987, 1989 1990, 1992, 1999, 2001, 2006, 2009 and 2021, while the other years are surplus. It has fallen sharply in recent years from 2019 to 2021 and a strong growth from 2022 to 2024. These results are consistent with those of Serinaldi [18] in the assessment of rainfall series and that of Lamah [11] in 2017 in the analysis of rainfall data of the Diani River watershed in Forest Guinea.

Fig. 3 shows the interannual global evolution of rainfall aggressiveness in the N'Zérékoré city. Its graphical analysis made it possible to identify three (3) levels of variation in climatic aggressiveness.

- a very wet period characterized by very high rainfall aggressiveness index values (4 years, or 10%) indicating a very active erosion;
- a high rainfall aggressiveness index (13 years, or 33%) indicating a strong erosion;
- and a low rainfall aggressiveness index (28 years, or 58%) corresponding to less aggressive erosion.

This situation shows that intense water erosion took place over 17 years on a period of 45 years in the N'Zérékoré city.

Fig. 4 shows the decadal variability in four periods of the aggressiveness of annual rainfall in the N'Zérékoré city (1980-2019). It appears from Fig. 4 that from 2000 to 2009 erosion was higher compared to other periods with a rate of 60% or 6 years of high rainfall aggression and 40% or 4 years of low erosivity.

For the periods of 1990 to 1999 and 2010 to 2019 the same rainfall aggression was recorded with respectively 60% or 6 years of low rainfall erosivity, 30% or 3 years of high rainfall erosivity. However, 10% or 1 year of very high rainfall erosivity for both periods was observed. We can also remark that from 1980 to 1989, we observe the highest rate in very high and low rainfall erosivity.

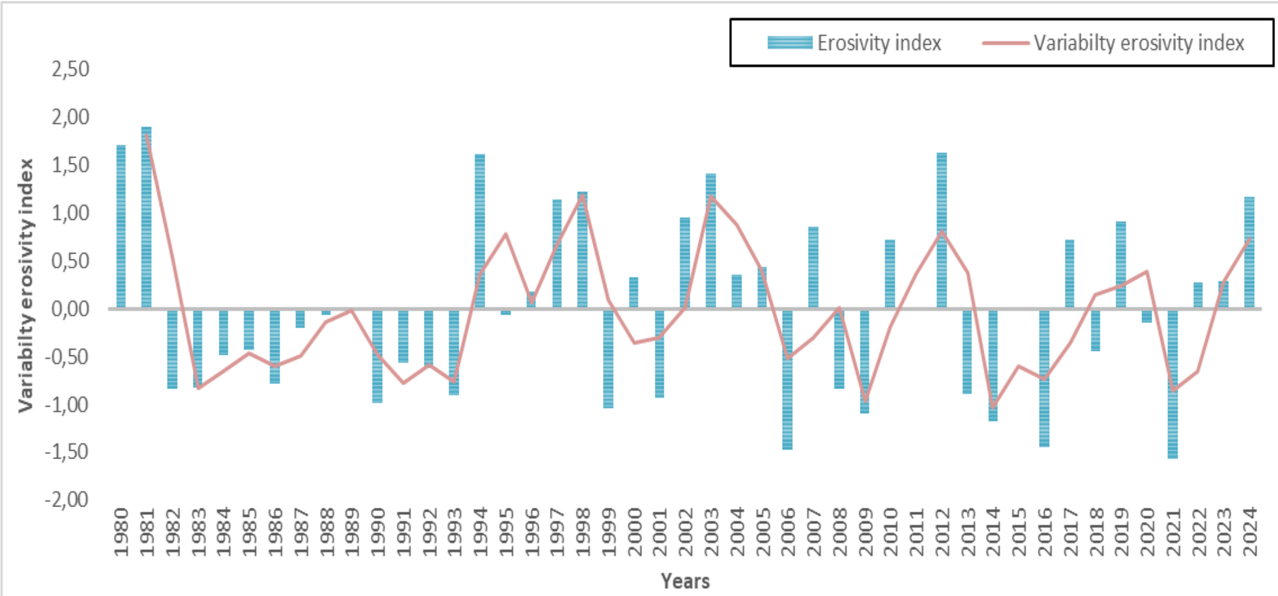

Fig. 3 Variability of the annual rainfall aggressiveness index in the N’Zérékoré city (1980-2024).

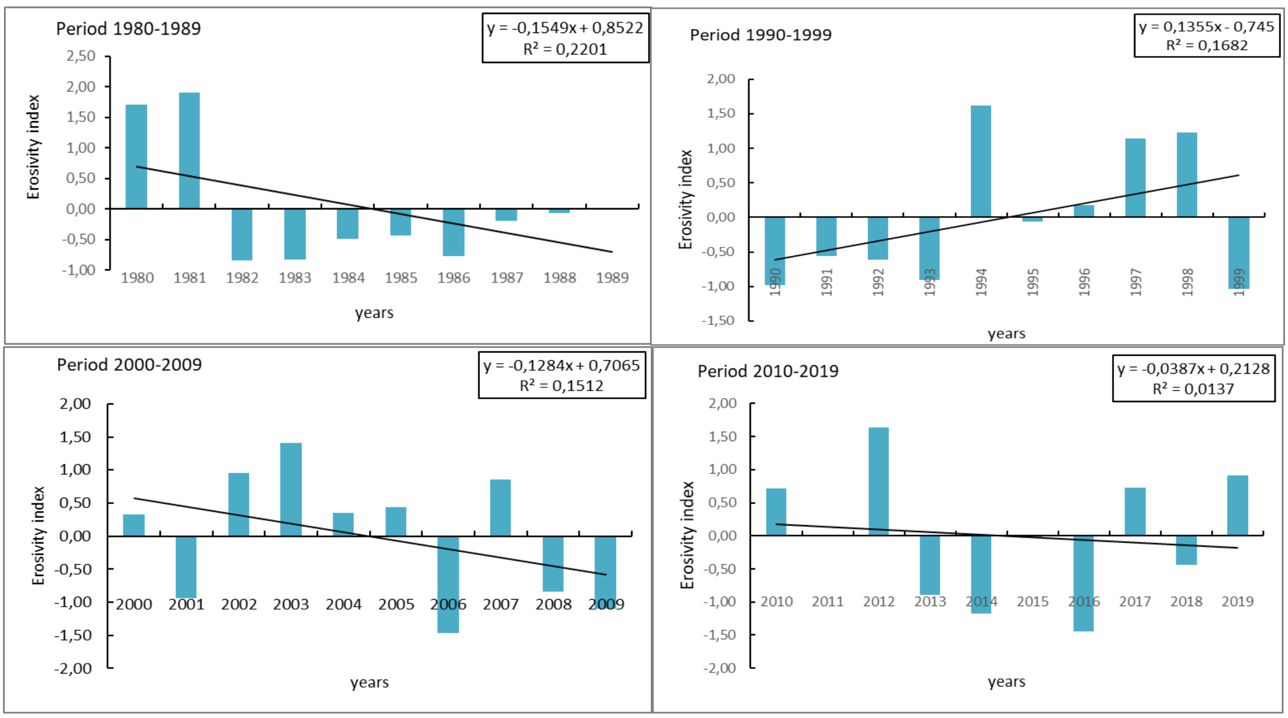

Fig. 4 Decadal variability in four periods of the aggressiveness of annual rainfall in the prefecture of N’Zérékoré (1980-2019).

Fig. 5 gives the annual evolution of rainfall aggressiveness with the Fournier index over 45 years in the overall city of N’Zérékoré. The graphical analysis allows understanding that erosivity is higher in 1981 with the very high index of 153.96 and the year 2021 records the lowest erosivity with an index of 42.46. This result is different from that found in Benin where the variation of the rainfall index is between 300 and 20 for ten years [10]. However, this figure shows that globally over the 45-year period, rainfall erosivity in the N'Zérékoré city remains very unstable. We observe a series generally centered around a stable average level,

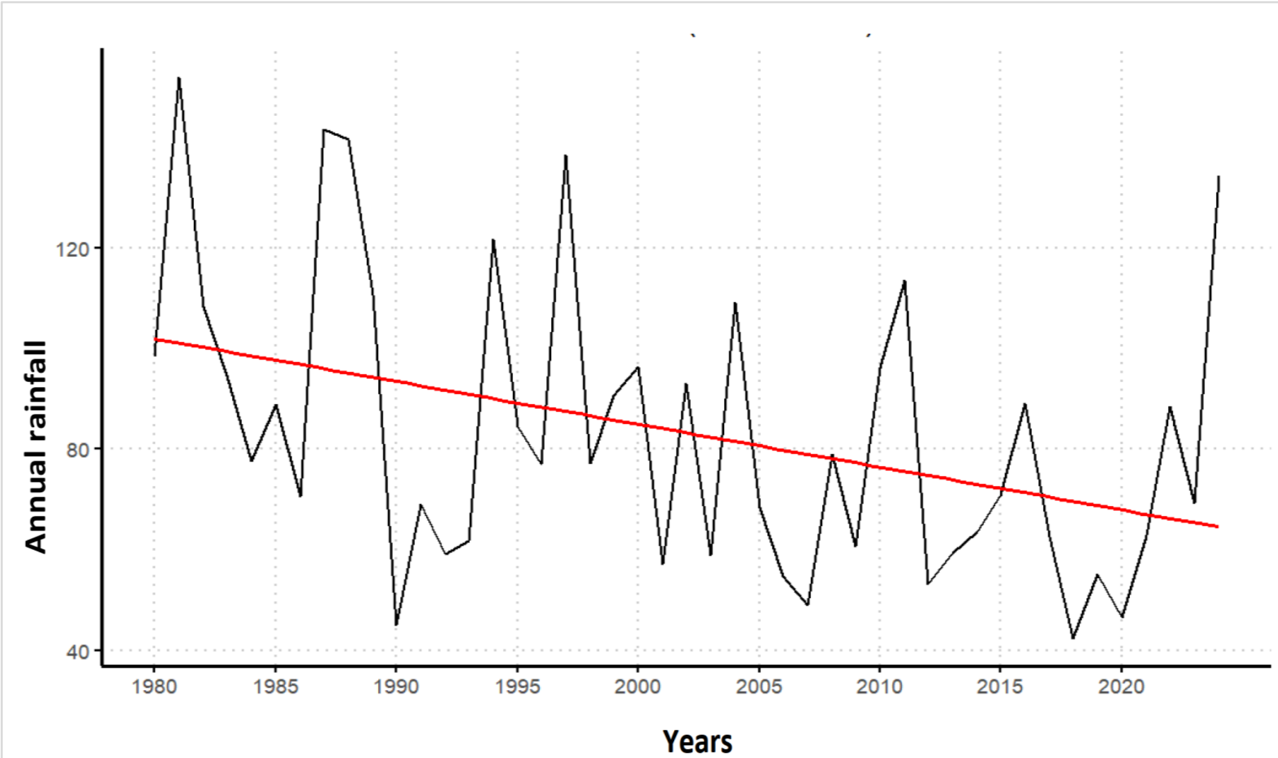

Fig. 5 Evolution of annual rainfall aggressiveness in the N'Zérékoré city (1980-2024).

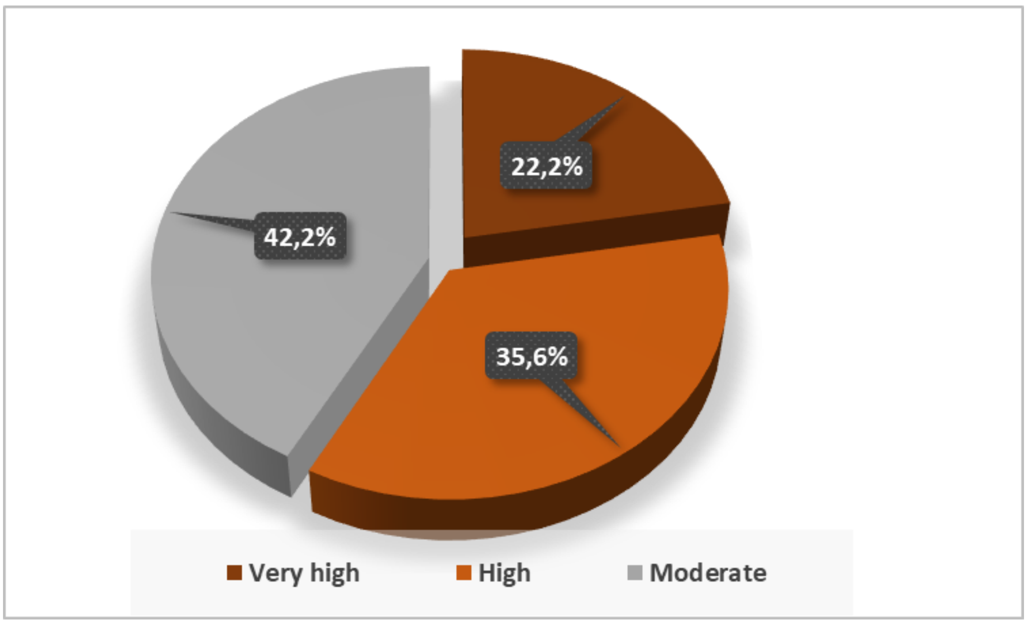

Fig. 6 Graph of annual rainfall aggressiveness in the N'Zérékoré city (1980-2024).

with notable interannual fluctuations. However, a slightly decreasing trend seems to emerge over time, which justifies more analysis of stationarity.

The result recorded in Fig. 6 shows three (3) levels of erosivity over a period of 45 years in the N'Zérékoré city. This result illustrates the level of erosivity is very high with a rate of 22.2% or 10 years, followed by the level of 35.6% or 16 years of strong erosion. The moderate erosivity level corresponds to 42.2% or 19 years. The very high erosivity levels represent 57.8% or 26 years of high erosion. The very high representativeness of high erosivity indicates that the N'Zérékoré city recorded very active erosion from 1980 to 2024 which reduces the fertility of agricultural land [12].

Fig. 7 shows the distribution of the annual rainfall erosivity level during forty-five (45) years in the N'Zérékoré city. By observing Fig. 7 we note that from 1980 to 1989 there is no moderate erosivity, however from 1990 to 2024 all the erosivity levels were observed, in addition the very strong and strong erosivity decrease while the moderate erosivity increases over time. This variation between the different erosivity levels is the instability and the scarcity of rain in the region of Forest Guinea [11].

The ADF (Augmented Dickey-Fuller) unit root test applied to the raw series is significant (p-value = 0.01), indicating formal stationarity. However, the decreasing trend observed in the series could introduce instability into the forecasts. To ensure the robustness of the model, a first differencing is applied to stabilize the average. After transformation by first differentiation, the obtained series no longer presents any apparent trend and oscillates around a constant average. This evolution visually confirms the stationarity of the differentiated series (see Fig. 8). The ADF test applied to the differentiated series is significant (p-value = 0.01), which allows rejecting the null hypothesis of non-stationarity. Thus, the transformed series is statistically stationary, which is an essential condition for the adjustment of an ARIMA.

Fig. 9 gives the combined analysis of ACF (Autocorrelation function) and PACF (Partial Autocorrelation Function) applied to the differentiated series.

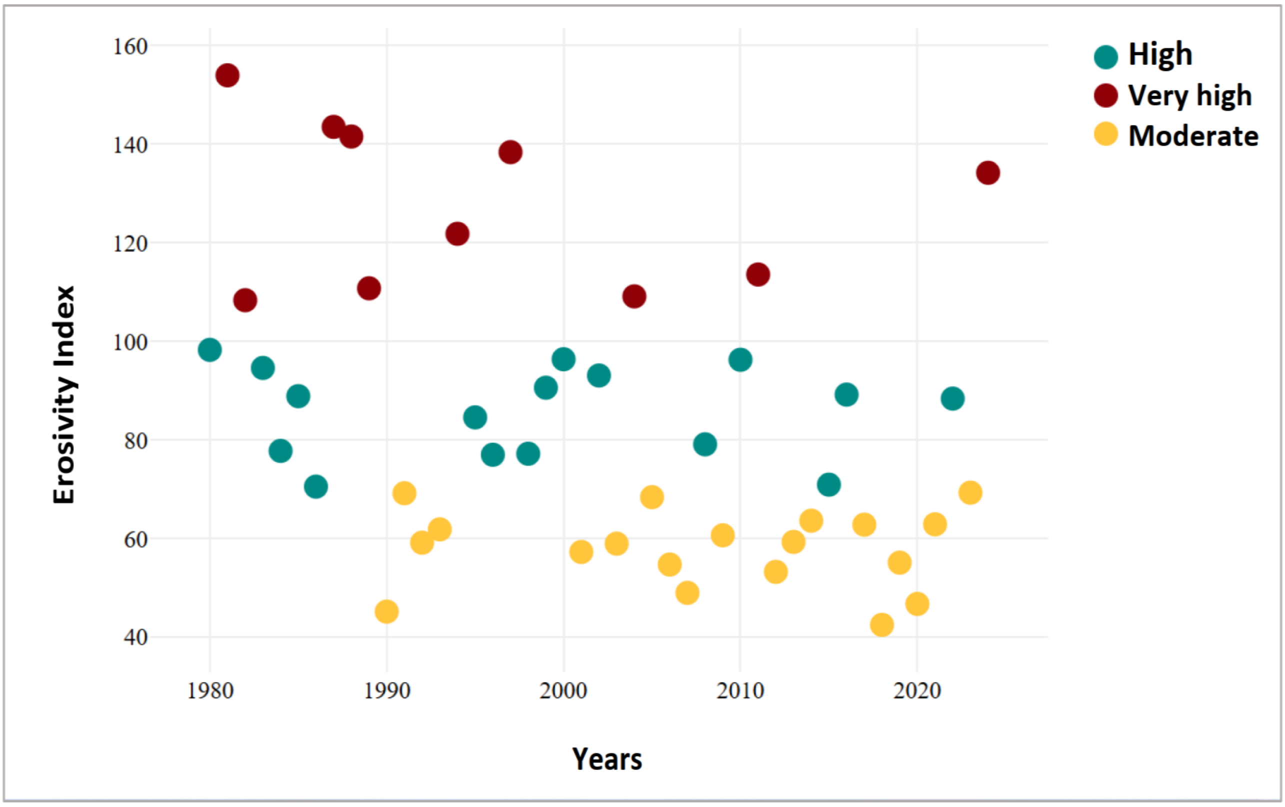

Fig. 7 Dispersion of annual rainfall aggressiveness from 1980 to 2024.

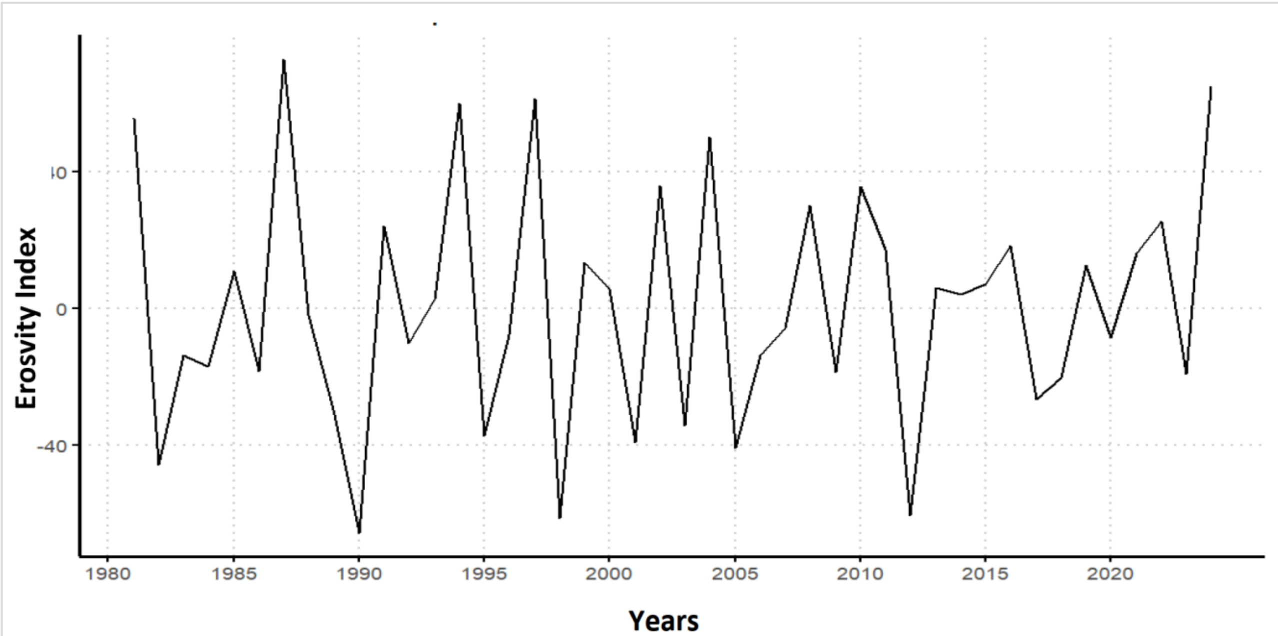

Fig. 8 Evolution of erosivity after differentiation.

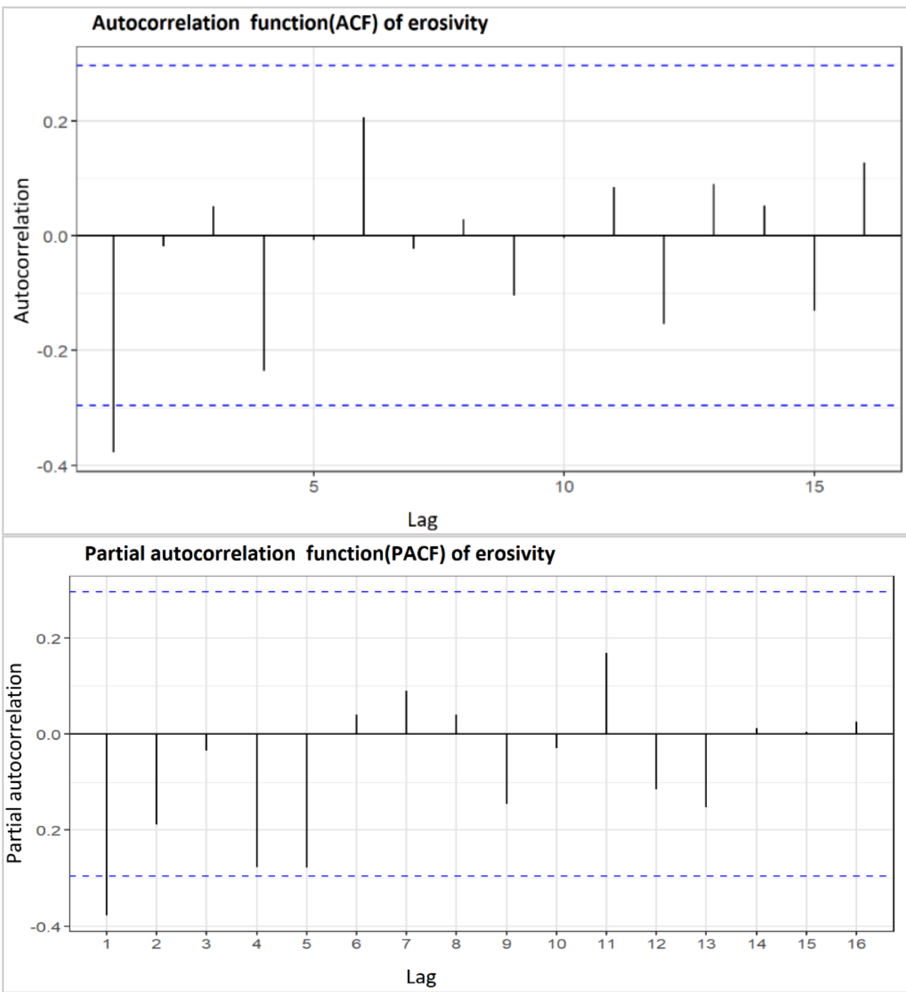

Fig. 9 ACF and PACF of erosivity.

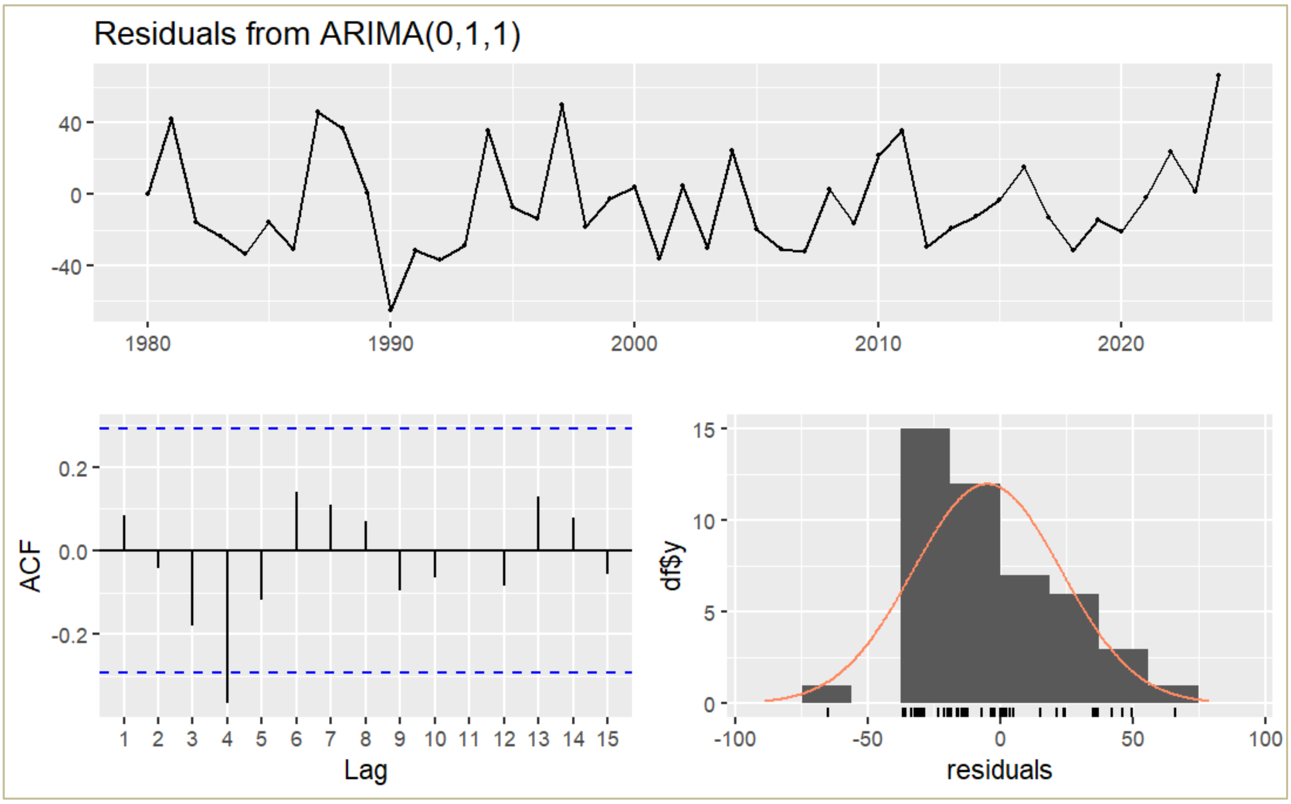

Fig. 10 Graphs of the residuals of the ARIMA model (0, 1, 1).

It reveals a progressive decrease in the ACF up to lag 14 (see Fig. 9), indicating a significant MA (Moving Average) component. The PACF (Fig. 10) shows sharp cuts from the first delays, suggesting a low-order AR (Autoregressive) component. These elements indicate that an ARIMA (p, 1, q) type model is appropriate.

The ARIMA (0,1,1) model, corresponding to a MA of order 1 applied to the differentiated series, selected on the basis of the analysis of the ACF and PACF. These highlighted a structure characteristic of an MA (1) type process, indicating that recent fluctuations in the erosivity index influence its evolution more than the past values. This behavior is consistent with the dynamics observed in environmental series, often subject to ponctual shocks rather than persistent dependence. The estimation of the MA parameter (1) gives a coefficient of -0.8625, with a standard error of 0.0842. This coefficient is highly significant, indicating a strong negative influence of the variation of the previous year on that of the current year, which suggests a mechanism of correction of the past disturbances.

The model residual variance is estimated at 829.1, which remains acceptable with respect to the natural variability of the studied phenomenon. The information criteria (AIC = 424.91; AICc = 425.21; BIC = 428.48) confirm the quality of the adjustment, guaranteeing a certain parsimony of the model. Finally, the estimating errors on the training sample, such as the RMSE (Root Mean Square Error) (28.15) and the MAPE (Mean Absolute Percentage Error) (31.16%), indicate satisfactory accuracy for forecasting purposes.

Through the analysis of the residuals ARIMA (0,1,1) model shows they do not present any trend or visible cyclical structure. The ACF does not reveal any significant autocorrelation, which is confirmed by the Ljung-Box test (Q^* = 12.299; df = 8; p = 0.1383), indicating that the errors can be considered independent. The histogram of the residuals (Fig. 10), associated with a normal density curve, suggests a distribution close to the normality, which is confirmed by the Jarque-Bera test for normality hypothesis as following (X^2 = 2.8663; df = 2; p = 0.2386)

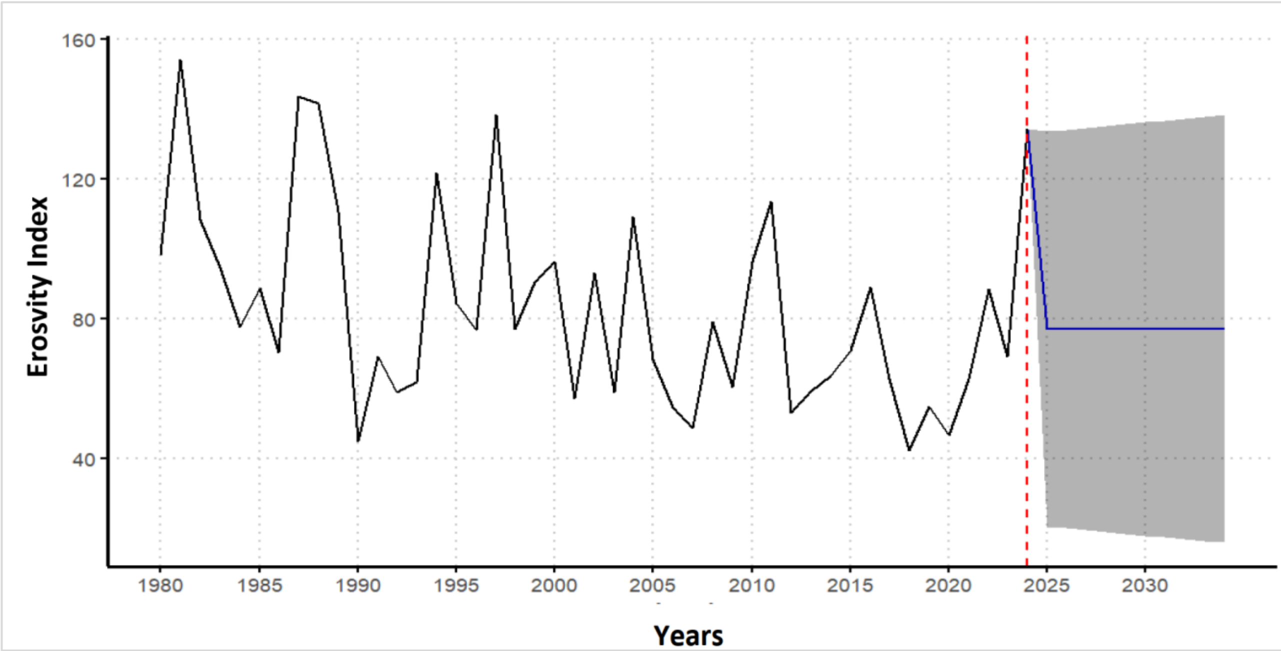

Fig. 11 Erosivity forecast for the next 10 years.

Furthermore, the Engle ARCH (Autoregressive Conditional Heteroskedasticity) test ($\chi^2 = 6.88$; ddl = 10; $p = 0.7369$) did not reveal any ARCH effect, which indicates a constant variance of errors over time, in other words, homoscedasticity. All of these results confirm that the classic assumptions of the ARIMA model—independence, normality and constant variance of residuals are respected, which validates the relevance of the adjusted model for forecasting.

Fig. 11 presents the erosivity index forecasts over a ten-year period using the ARIMA (0,1,1) model. Historical data are shown in black, forecast values in blue, and the 95% confidence interval in gray. The model anticipates relative stability in the erosivity index, although uncertainty increases with the time horizon, as evidenced by the progressive widening of the forecast interval. The ARIMA (0,1,1) model predicts a stable erosivity index around 77.14 over the period 2025-2034. This consistency suggests a lack of deterministic trend in the future evolution of the phenomenon. However, the progressive widening of the confidence interval highlights increasing uncertainty as the forecast horizon becomes longer. This uncertainty reflects the random nature of environmental fluctuations influencing erosivity.

4. Conclusions

The N'Zérékoré prefecture is a major agricultural actor in Guinea's economy. Its production heavily depends on the rainy seasons. However, these rains, essential for the proper functioning of ecosystems and agrosystems, are also a major factor in water erosion, threatening the region's agricultural soils. The study highlights the variability of rainfall erosivity, linked to climatic hazards and the vulnerability of the local environment.

The results show from 1980 to 1989, the region experienced a very high peak in erosivity (70%) of the years observed, while the period 2000-2009 also showed high erosivity (60%). Conversely, the decades 1990-1999 and 2010-2019 were characterized by lower levels of rainfall aggressiveness, with 60% of the years marked by low erosivity. Over the 45-year observation period, three levels of aggressiveness emerged: very high (22.2% of the years), high (35.6%) and moderate (42.2%).

The ARIMA (0,1,1) model forecasts indicate a stability of the erosivity index around 77.14 for the period 2025-2034. After several decades of instability and marked erosion, these prospects suggest an improvement and better management of water erosion control facilities in the city. This encouraging trend represents an opportunity to strengthen the sustainability of agricultural practices and preserve local natural resources.

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