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Geosystemic Impacts of the Extreme Rainfall Linked to the El Niño 2015/2016 Event in Northern Paraná, Brazil

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Abstract: The El Niño episode between September 2015 and February 2016 caused abundant rainfall in the state of Paraná in southern Brazil. In this study, we map the greatest magnitude of this climatic event and the respective geosystem responses in the landscape. For this purpose, 32 precipitation series were analyzed (1981–2016). The parameter most indicative of extreme rainfall events during the El Niño period was the six-month accumulated precipitation. The return period (RP) of this parameter was calculated and spatialized using kriging. The results show that a longitudinal strip of 450 km by 140 km had rainfall with RP > 30 years, reaching maximums greater than 150 years. Surveys performed in the field, with aerial images, official sources and media news show a great diversity of effects caused by rainfall, such as road blockages, interruption of water and power supply, and erosion in urban and rural areas. It is concluded that the stability of regional geosystems was disrupted because of extreme rainfall values, so that the northwest region of Paraná had less resilience compared to the north-central and Pioneer North regions, due to the differences between the lithologies and soils of these regions.

Keywords: erosion; flooding; resilience; return period; connectivity

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1. Introduction

The occurrence of extreme rainfall in the last four months of 2015 and the first two months of 2016 in north-central and northwestern Paraná, a state located in the southern region of Brazil, was particularly problematic due to its impacts on the local human activities. This was related with the El Niño event of this period, classified as "strong" by the Oceanic Niño Index (ONI) values and by some authors [1,2], causing abundant rainfall for consecutive months [3,4], with impacts on several geosystem elements.

In order to analyze the connections between the El Niño event of 2015/2016 (EN 15–16) and the respective geosystem responses in the northern region of Paraná, the following objectives were set: (i) to characterize the El Niño episode; (ii) to evaluate rainfall databases for the period of the episode, seeking to determine which statistic(s) reflects the process intensity; (iii) to calculate return periods for the recorded rainfall, as a means of identifying rarity through frequency; (iv) to map the distribution of these extreme rainfalls; and (v) to describe examples of disturbances caused to geosystem features, using various sources.

The geosystem is a traditional theoretical approach in physical geography, resulting from the application of the General Systems Theory [5] in this branch of geography. A system can be understood as an organized whole, composed of several parts or variables that interact with each other, so that the whole is different from the sum of the parts [5]. The geosystem is composed of four spheres: atmosphere, hydrosphere, lithosphere, and biosphere [6], as well as their interactions, exchanges of energy and matter between them.

There are two specific systemic principles that support our exercise—the hierarchy among variables and the concept of threshold. The former relates to the resilience of landscape components, which refers to the ability to experience an adverse event and self-reestablish the characteristics (forms, structures) and functions [7]. Thus, in this study, we evaluated that, during EN 15–16, an expressive variation in the state of one of the controlling variables (climate) led to a series of adjustments in landscape response variables. In addition to the hierarchical organization, it is assumed that a geosystem threshold was exceeded, since the input of water into the system through the volume and intensity of rainfall altered many variables of the geosystem, and without anthropic action, such changes would be irreversible. This assumption presumes that the variables would be in conditions of relative stability.

2. Methodology

The summary of the procedures performed in this research is presented in Figure 1. The rainfall data were obtained from in situ rainfall stations and Rainfall Estimates from Rain Gauge and Satellite Observations (CHIRPS). Rainfall stations of the National Institute of Meteorology (INMET), the Agronomic Institute of Paraná (IAPAR), the Water and Land Institute (IAT), and the National Water Agency (ANA) were considered. The setup and analysis of the rainfall data supported the calculation of the event's return period (RP) for each station, via probability models. RP values were afterwards spatialized via interpolation (kriging), resulting in a detailed spatial–temporal description of the rainfall occurred between September 2015 and February 2016.

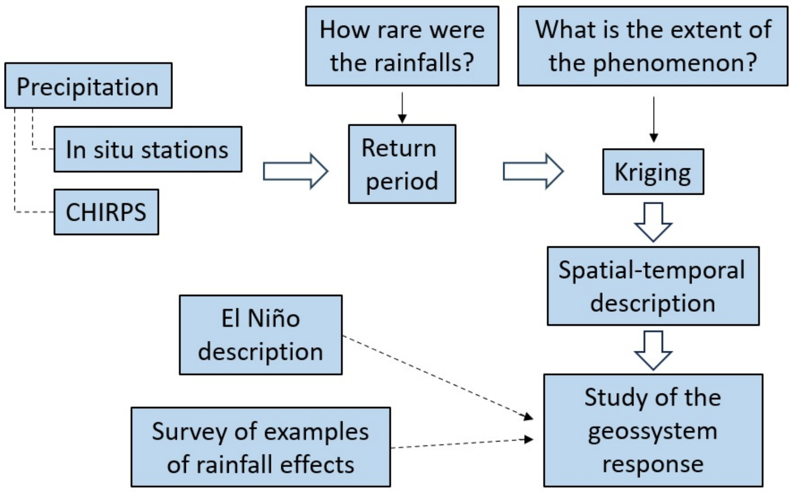

Figure 1. Methodological flowchart for the study of the geosystemic impacts of the extreme rainfall linked to the 2015/2016 El Niño in Northern Paraná, Brazil.

In addition, a description of EN 15–16 was made based on the Southern Oscillation Index (SOI) and a survey on the effects that the rainfalls of the period brought on geosystem components was carried out. These data served as the basis for discussions about the effects of EN 15–16 on the geosystems in the northern region of Paraná.

2.1. Study Area

The study area was defined during the acquisition and processing of data, since the spatial extent of occurrence of the voluminous rainfall was not known a priori, considering as a reference the period between September 2015 and February 2016. Thus, a search for data was conducted, starting from the north-central region of Paraná until the phenomenon of heavy rainfall was no longer found. This procedure resulted in an area that includes a large part of the interior of the Paraná state, parts of the states of São Paulo and Mato

Grosso do Sul, and a small part of Paraguay, between longitudes 50° W and 55° W and latitudes 21.5° S and 25.5° S (Figure 2).

The Paraná regions defined in this study do not fully match the regional division proposed by the Brazilian Institute of Geography and Statistics [8]. The western, central and eastern parts of the study area correspond to the northwest, north-central and Pioneer North regions, respectively. Two geosystem units (one corresponding to the northwest region and the other to north-central and Pioneer North regions, as defined by [9]) are covered.

For the description of EN 15–16, literature on the subject was analyzed to identify which atmospheric conditions led to the formation of abundant rainfall during the September 2015–February 2016 period. Moreover, this period was defined by analyzing Southern Oscillation Index (SOI) obtained from [10].

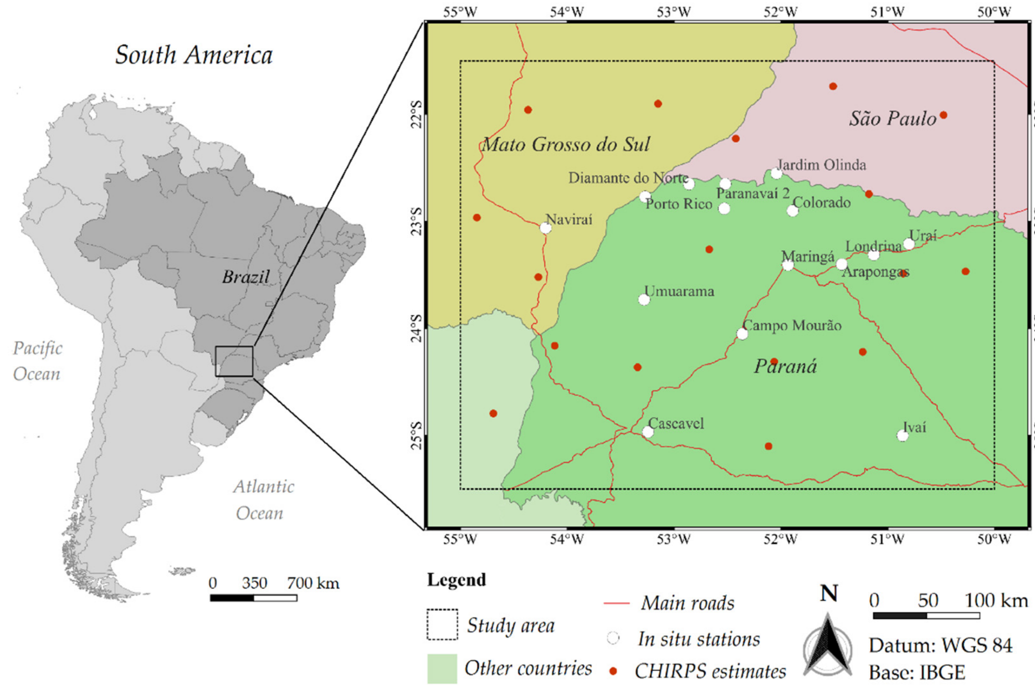

Figure 2. Location of the study area (Northern Paraná, Brazil), rainfall stations and CHIRPS estimates used in the study. Sources: [8,11].

2.2. Rainfall Analysis

Rainfall data were obtained from recorded (or in situ) instrumental data and from a global base of estimated values. Priority was given to in situ measurements, whose data were provided by [11]. However, since the analyses required continuous and error-free historical series for the period covered by EN 15–16, many of them were pre-evaluated and discarded. To obtain a grid of points that allowed the spatial evaluation of the phenomenon, we used data from the CHIRPS project, which provides a database of global estimates with a resolution of 0.05°, and is generated from conventional records and satellite observations [12]. Fifteen series were obtained from in situ measurements and seventeen from the CHIRPS project (Figure 2 and Table 1). The hypothesis of intense landscape changes due to rainfall during EN 15–16 was tested by analyzing daily, monthly, and cumulative data. The six-month cumulative was the selected statistic, and the results of this exploratory analysis are presented in the results section.

Table 1. Rainfall stations used to obtain precipitation series—in situ measurements.

Municipality/ Federative Unit	Institution Responsible	Code	Longitude	Latitude	Altitude (m)
Maringá/PR	INMET	83767	−51.932	−23.405	549
Colorado/PR	IAT	2251033	−51.89	−22.9	490
Umuarama/PR	IAPAR	2353008	−53.28	−23.73	400
Jardim Olinda/PR	IAT	2252013	−52.04	−22.55	260
Campo Mourão/PR	INMET	83783	−52.36	−24.05	616.4
Londrina/PR	INMET and IAPAR	83766 and 2351003	−51.13	−23.31	566
Ivaí/PR	INMET and IAT	83811 and 2550006	−50.86	−25	808
Arapongas/PR	IAT	2351048	−51.43	−23.4	810
Uraí/PR	IAT	2350023	−50.8	−23.21	440
Paranavaí/PR	IAT	2252027	−52.53	−22.88	510
Paranavaí/PR	IAT	2252017	−52.52	−22.65	345
Diamante do Norte/PR	IAT	2252015	−52.86	−22.65	340
Porto Rico/PR	IAT	2253002	−53.27	−22.77	250
Naviraí/MS	ANA	2354000	−54.19	−23.06	345
Cascavel/PR	IAT	2453056	−53.24	−24.96	680

A probabilistic analysis was performed to determine how rare the six month accumulation of rainfall was, based on the exceptionality observed in the period. Historical series were used for the adjustment of statistical distributions and parameters were applied to calculate the probability of an event equal to or greater than that observed in February 2016 for each series. It was noted that the gamma distribution was the most appropriate, therefore it was necessary to obtain the shape (γ) and scale (β) parameters, specific for each series.

The length of all the historical series and the existence of gaps were verified, resulting in a 36-complete-years-period set for this work, between January 1981 and December 2016. After calculating the probability for each of the 32 historical series, the return period (RP) was calculated based on the following equation:

$$\mathrm{RP} = \frac{\frac{1}{\mathrm{P}}}{12} \tag{1}$$

where RP is the return period (in years) and p is the probability. The value 12 is for conversion from months to years.

2.3. Phenomenon Spatialization

The RP values and their respective coordinates were used to generate a continuous surface of the rainfall RP occurred between September 2015 and February 2016. The interpolation method used was the geostatistical method, which is based on a series of assumptions, such as spatially homogeneous distribution of data and variance. For variogram analysis and spatial autocorrelation model fitting, the gstat package [13], operational in R environment [14] was used. After adjusting the experimental variograms, kriging was performed in SAGA software [15].

To meet the kriging assumptions, initially, the dependent variable RP was transformed by its natural logarithm. Subsequently, given the existence of a spatial trend, the data were adjusted using polynomial regression. The residues of this regression were used as the database for kriging, which adopted the following model:

$$a + b \cdot \left[1 - e^{-\left(\frac{h}{b}\right)^2}\right] \tag{2}$$

where a is the nugget effect (0.1209), b is the range (0.82879) and h is the distance (range and distance in degrees). After kriging the regression residues, this surface was added to the area resulting from the initial polynomial interpolation. It is noteworthy that the observed nugget effect was relatively expressive, that is, there was a large local variability, which was not explained by the spatial autocorrelation structure.

2.4. Sample Survey

A search was conducted in news reports and official sources about events resulting from the rainfall during EN 15–16 in Paraná state; photographic records obtained during fieldwork were also used. High-resolution orbital images from Google Earth were used to compare the landscape before and after the event. Following the analysis of these examples, a conceptual scheme of the variables, processes, and interrelationships involved was elaborated from a systemic perspective.

3. Results and Discussion

3.1. The 2015–2016 El-Niño

The El Niño-Southern Oscillation (ENSO) is the main source of global interannual variability [16]. The different signs of precipitation and temperature anomalies observed, in addition to the heating area of the Pacific Ocean, reflect the extent of its interference in atmospheric conditions. In South America, such anomalies are mainly associated with factors such as the displacement of the Walker Cell, the strengthening of the subtropical jet stream and a wave train from the Pacific to southern South America [17].

The El Niño episode that occurred between 2015 and 2016 (EN 15–16), since its prediction, had its intensity compared to the strongest events of the 20th century [1]. Considering the precipitation values for the September–November quarter, the negative anomalies (below average rainfall) over the northern portion of South America (Amazon and Northeast and Midwest regions of Brazil) were more intense than the El Niño episodes of the years 1982 and 1997 [4]. Also, according to the same authors, in this quarter, the positive anomalies (above-average rainfall) in the southeast region of South America were not as spatially expressive as in the previous episodes mentioned.

Despite the differences between EN 15–16 and other episodes, in the former there was a higher frequency of cyclone formation in subtropical latitudes of the Atlantic Ocean, leading to moisture convergence over southeastern South America [4]. Cyclogenesis also contributed to the canalization of the low-level jet stream east of the Andes, increasing moisture transport from the tropical to the subtropical region. Finally, [4] further mention that in EN 15–16 there was a positive atmosphere circulation anomaly of geopotential height in the Pacific Ocean in the proximity of South America, considered important for the positive precipitation anomalies in southeastern South America.

Observing the data of the Southern Oscillation Index [10], one can notice the evolution of EN 15–16, whose component of atmospheric circulation, associated with the differential heating of the waters of the equatorial Pacific Ocean, evolved from positive to negative values, since May 2013, reaching lower values, especially after March 2015 (Figure 3). The period between September 2015 and February 2016 presented the greatest ENSO intensity, in its negative phase of the SOI, a period that coincided with abundant rainfall in the northern region of Paraná.

3.2. Analysis of the Rainfall Series

Analysis of the daily rainfall data showed that the highest value of the historical series of Maringá (1980–2017) occurred on 1 November 2016 (Figure 4A). However, this event was only 7.26% greater than the occurrence verified on 19 June 2012 (157 mm). The occurrence of this event also has a spatial context, because although the daily rainfall was the most significant in the historical series of Maringá, this was not reported in other evaluated series. Therefore, although the record of 1 November 2016 was locally relevant, the daily rain on that date was not that expressive for the entire northern region of the state. A comparison equivalent to that can be seen in [18], for the Alto Alegre station (code 2251033, municipality of Colorado, PR) (Figure 4). Considering the same period evaluated in this work, the daily (Figure 4A) and monthly (Figure 4B) precipitation were not extraordinary, though the six months accumulate presents a RP higher than 100 years (Figure 4C).

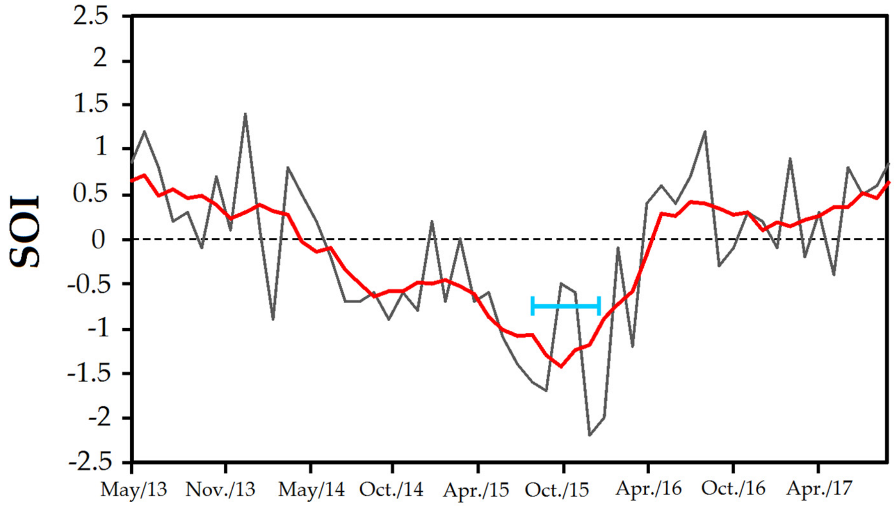

Figure 3. Southern Oscillation Index (SOI) for the period from May 2013 to October 2017. The red line represents a seven-month moving average. The blue line indicates the period from September 2015 to February 2016. Data source: NOAA [10].

By analyzing the monthly values (Figure 4B), we observed that January 2016 was the third rainiest month in the historical series (419.8 mm), behind February 1997 (446 mm) and January 1990 (421.6 mm). Analyzing the historical series, in several other moments there were months with precipitation above 350 mm. Thus, the monthly values interpreted in isolation seem not to have been relevant during EN 15–16.

Based on the series of monthly values, consecutive rainy periods were analyzed, so that for EN 15–16 the following sequence was observed: 236.7 mm in September 2015; 312.2 mm in October 2015; 369.6 mm in November 2015; 327 mm in December 2015; 419.8 mm in January 2016; 382.1 mm in February 2016. In these six months, the rainfall cumulate was 2049.4 mm. A statistic sum of the rainfall value of the current month plus the five previous months was generated (Figure 4C). Considering this sum, since 1980 there has been no similar event, with the second largest event occurring in 1983 (difference of 524.1 mm: −34.36%) and the third in 1997 (difference of 563.1 mm: −37.88%), both periods that were also under the influence of El Niño. The 2049.4 mm cumulate in February 2016 was so impressive that it presents a 4.43 standard deviation above the mean, based on the 1980–2017 period.

When analyzing historical series from other locations referred to in Table 1, similar patterns were observed, in which the isolated daily and monthly rainfall did not seem to show an extraordinary event, but when performing the sum of these six months, the series indicated peaks similar to that presented in Figure 4C. Thus, the sum of the rainfall for six months was taken as the variable representing the extraordinary rainfall arising from EN 15–16.

Similarly with this study, the six-month cumulative rainfall was used by [19–21] as a climatic precursor for landslides in the southern Italian Apennines. These studies showed that the piezometric fluctuations and the landslide activity in the slope have a strong relation with the seasonal climate. In particular, the rainfall cumulated between 160 to 180 days is very related to deep and slow landslides (deeper than 3 m).

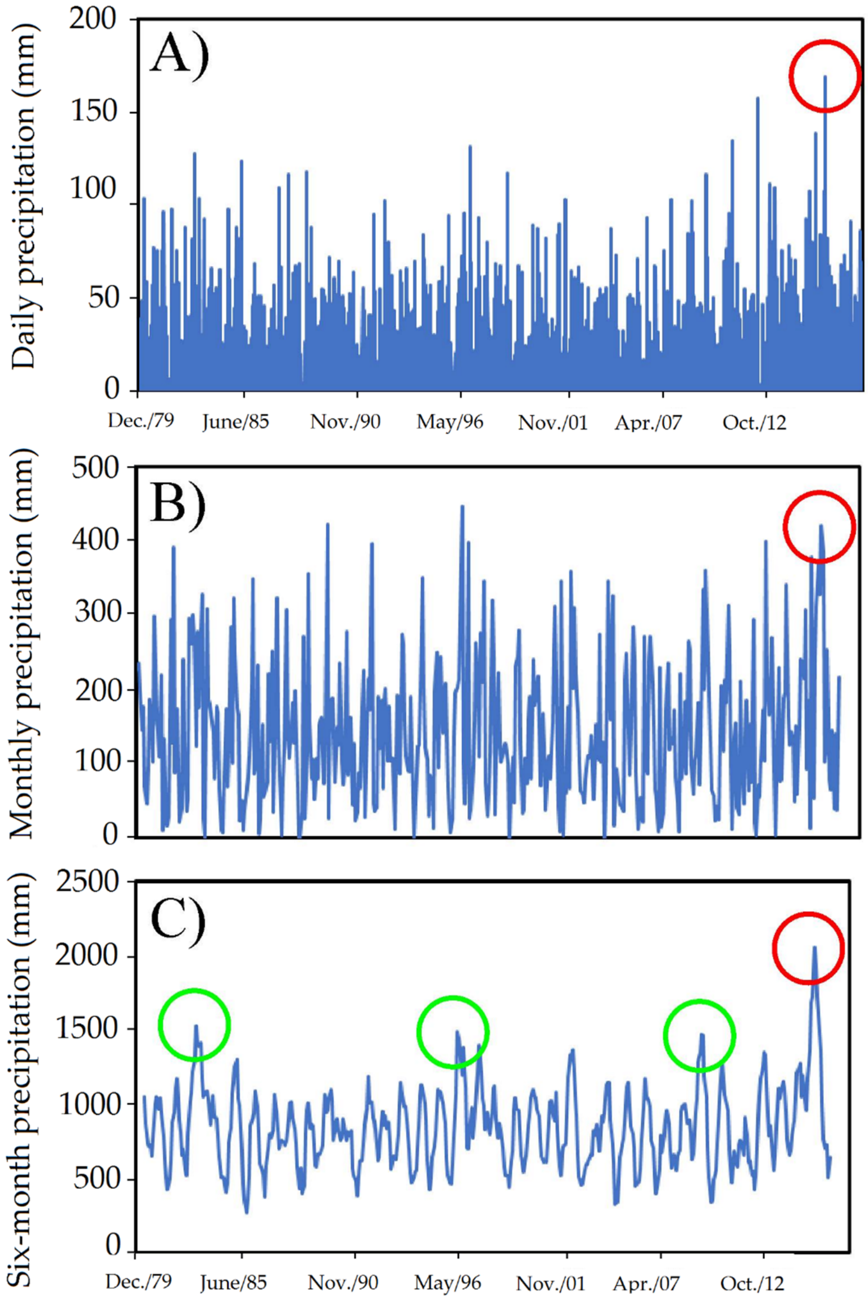

Figure 4. Precipitation in Maringá, PR: 1980–2017. (**A**) Daily rainfall; (**B**) monthly rainfall; (**C**) Cumulative rainfall (six months). The red circle indicates EN 15–16, and the green circles in (**C**) indicate the years 1983, 1997 and 2010. Data source: Maringá Main Climate Station (ECPM)/INMET.

3.3. *Spatial-Temporal Description of Rainfall*

Table 2 presents the locations where the observed RP was greater than 30 years, with emphasis to the stations in Maringá, Londrina, Colorado and Arapongas, which obtained RP values greater than 100 years. The greatest accumulated rainfall in the period between September 2015 and February 2016 occurred in Londrina (2092.1 mm) and the second highest in Maringá (2049.4 mm). Although the absolute value was higher in Londrina, as the calculation of the RP considers the distribution adjusted to each historical series, a higher value of accumulated rainfall does not necessarily lead to a higher RP.

Table 2. Rainfall cumulated between September 2015 and February 2016 and RP (return period) in rainfall stations in Northern Paraná (showing only the stations with RP higher than 30 years).

Municipality/ Federative Unit	Code	Accumulated Rainfall (September 2015–February 2016) (mm)	RP (Years)
Maringá/PR	83767	2049.4	178.38
Londrina/PR	83766 and 2351003	2092.1	148.31
Colorado/PR	2251033	1767.7	106.6
Arapongas/PR	2351048	1957	103.9
Porto Rico/PR	2253002	1445	70.8
Paranavaí/PR	2252027	1573.7	43.69
Naviraí/MS	2354000	1725.5	43.68
Umuarama/PR	2353008	1712.3	41.56
Diamante do Norte/PR	2252015	1527.5	39.33

The comparison between the data in Table 2 and the stations geographical distribution (Figure 2) shows that the highest RP values (above 150 years) occur in the central part of Northern Paraná between the cities of Maringá and Londrina, where the rainfall was higher (Figure 5).

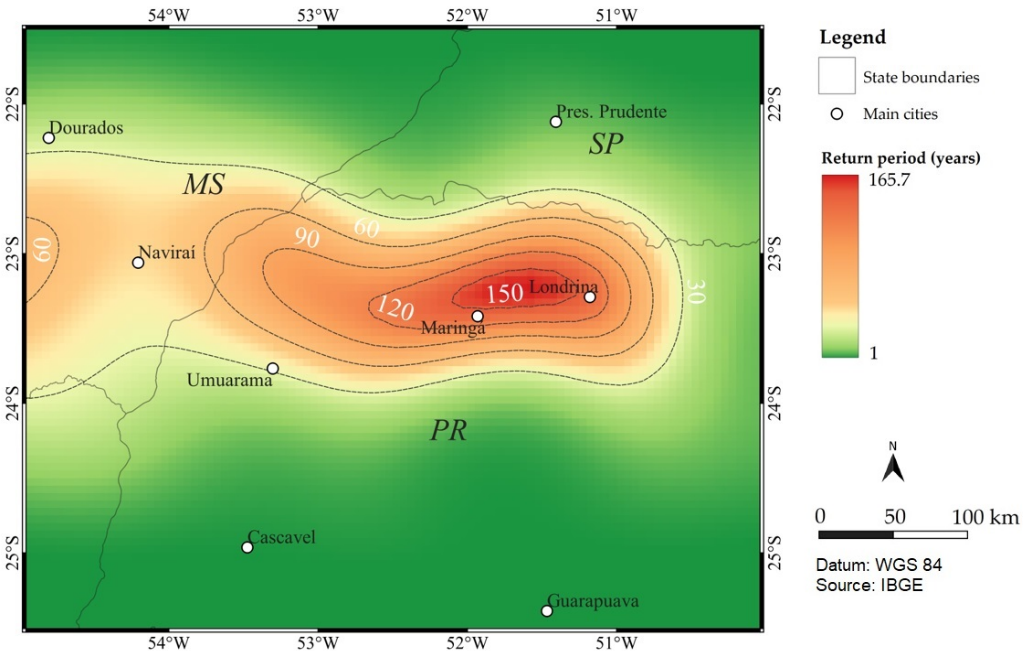

Figure 5. Rainfall cumulate (September 2015 to February 2016) RP (return period) in Northern Paraná, Brazil.

Besides this core area where the rainfalls were larger (RP > 150 years) and taking into account accumulations with RP > 30 years, a study area was identified whose eastern border begins about 60 km east of the municipality of Londrina, extending westward to the south of Mato Grosso do Sul state. Latitudinally, the area extends between the Paranapanema River at the north and the boundary of the municipality of Umuarama at the south. Considering these limits, the rainfall values were extraordinary (RP > 30 years) in an area of about 63,000 km^2 (450 km by 140 km). The northern edge of this area coincides approximately with the boundary between the states of Paraná and São Paulo, entering the state of Mato Grosso do Sul to the west. The southern border, on the other hand, is approximately north of the city of Umuarama, in the Paraná state. This spatial delimitation of this event [22] exemplifies the functional connectivity [23–25] characterized by the temporal identification of the process responsible for the transfer of water and sediments with notorious repercussions on the landscape [26].

3.4. Landscape Disturbance

The continuous and intense rainfall that started in September 2015 had the most evident effects on the landscape at the start of 2016. With soil conditions already close to water saturation, the extreme daily rainfalls in the first half of January 2016 led to intense surface runoff over the slopes, causing flooding in the region. Social problems ensued from this, among the most impactful being the interruption of water supply in many municipalities in the region, including the two most populous: Maringá (454,000 inhabitants) and Londrina (565,000 inhabitants).

In some cases, this interruption occurred due to the flooding of the infrastructure of the public collection system of urban supply. In Maringá, about 85% of the population were left without water supply [27]. According to data from the Paraná Sanitation Company [28], the interruption of the collecting in the Pirapó River was on 12 January 2016, and the normalization of the supply in Maringá occurred only on 22 January 2016.

Still, according to the media [27], on 13 January 2016, 36 municipalities in Paraná state had cases of torrents, landslide and flooding, with records of displaced, homeless and injured people. An emergency status was declared in Londrina on 12 January 2016, and 64 houses, four schools and eight basic health units had structural problems caused by the rainfall. In this municipality, there were also registered interdictions of five bridges and 2675 properties without power supply. As a result of the interruption of roads due to erosion, bridge collapse and flooding, waste collection was suspended in Londrina and there was a temporary interruption of public transportation to many districts of the city. Regarding the water supply, the collecting operated at only 30% of capacity, due to the rise in the water level of the Tibagi River [29], the local source.

The EN 15–16-related rainfall also caused traffic interdiction (total or partial) on several municipal, state and federal roads, for reasons such as rising river levels, erosion caused by surface runoff, bridge collapses and landslides. In most cases, the interdictions were temporary, with traffic being re-established after the reduction in the rivers' discharge. However, in other situations, traffic took between weeks and months to be normalized, due to the combination of the need for emergency work and continued rainfall, which made it impossible for the state and concessionaires to act quickly.

In the northwest region of Paraná several roads were already blocked in November 2015 [30], while in the north-central and Pioneer North regions, problems of this order occurred mainly after the intense rainfall in early January 2016 [27,29]. Possibly, the reason for this difference is due to the characteristics of these regions' soils. In the northwest sedimentary formations (mainly sandstones) occur, where the soils have a higher sandy fraction and are more friable when compared to the soils developed on the igneous formations of the other areas of the northern Paraná. This shows that the resilience [31] of this geosystem component—as a spatial unit [9]—in the northwest of the state is lower when compared to the geosystem in the north-central and Pioneer North regions. Nevertheless, both regions presented geosystemic functions compromised with the occurrence of these extreme events, but under different conditions.

The erosion resulting from excessive surface runoff in rural areas was another effect of the voluminous and accumulated rainfall throughout the evaluated period. In cases where the terrace system did not support runoff, erosive features such as gullies and rills were developed. Large erosional features occurred in sugarcane plantation areas was near the municipality of Nossa Senhora das Graças (Figures 6 and 7), where the September 2015–February 2016 cumulate rainfall RP was close to 92 years (Figure 5). When comparing aerial images obtained in July 2013 (before EN 15–16) and April 2016 (after EN 15–16) it is possible to observe the development of large erosive (Figure 7A), and depositional (Figure 7B) features during the period.

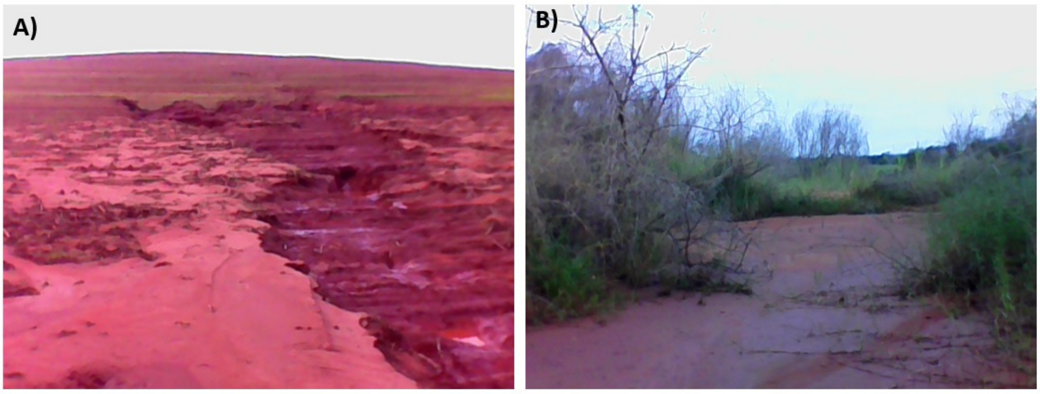

Figure 6. (**A**) Linear erosion (rills and gullies) developed in a sugarcane plantation area in the municipality of Nossa Senhora das Graças, Paraná state, Brazil; (**B**) sediments deposited downstream, in the same basin of the observed erosional features; dead vegetation is observed between the sediments and the margin of the river plain. Date of the photographs: 23 May 2017.

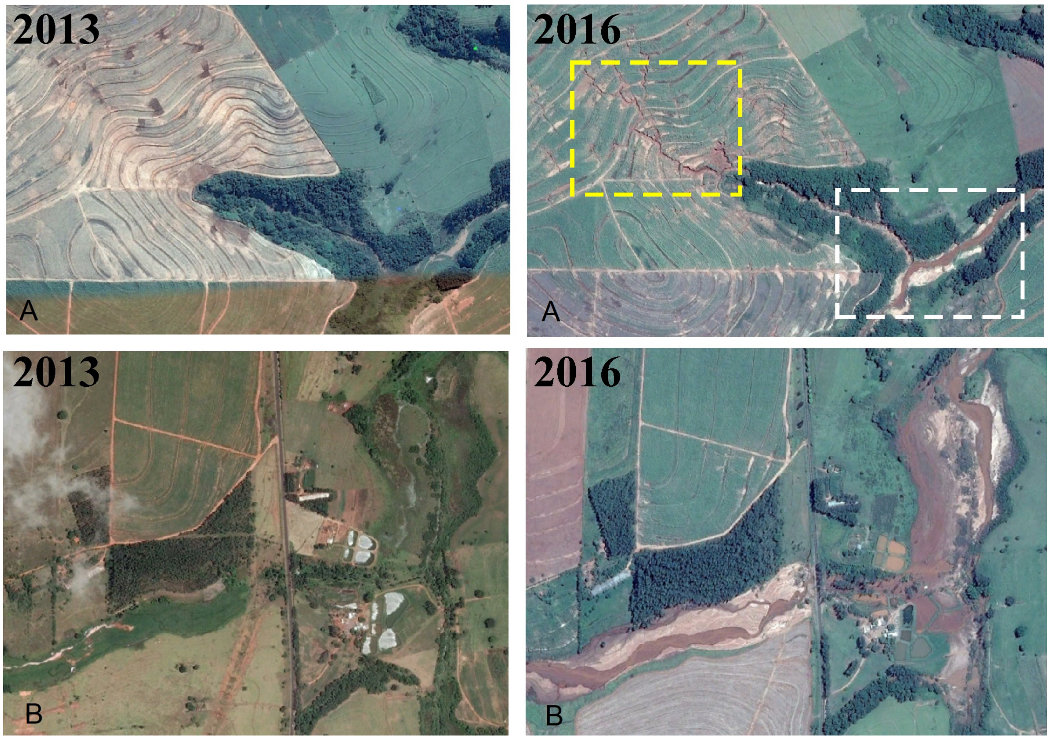

Figure 7. Aerial view of pre and post EN 15–16 landscape in a rural area of Nossa Senhora das Graças, Paraná state, Brazil: (**A**) at the upstream sector, extensive and deep linear erosional features (gullies) were developed on a sugarcane plantation (yellow square) as well as deposition of sediments generated on the slopes (white square); (**B**) at the downstream sector of the same basin, the depositional processes were predominant. Source: Google Earth.

The gully erosion exceeded 700 m in length, triggered evidence of lateral, longitudinal, and vertical connectivity. Initially, the rainfall intensity caused lateral connectivity in sections of the slope with sediment transport into the channel, followed by longitudinal connectivity, which resulted in a large flow of sediments deposited both in the floodplain and in the Santo Inácio river. The deposition of sediments (up to 3 m in thickness, as observed in loco) buried reservoirs (fish farming) and swine farming structures (Figures 6 and 7). With the rise in the water table and the large volume of sediments, and, consequently, the increase in vertical connectivity, the floods also caused the eradication of riparian vegetation (Figure 6B).

Significant erosive processes occurred in urban areas of the municipality of Umuarama (Figure 8). A sports center had problems with erosive processes previously, as observed in the aerial images. However, with the extreme rainfall concentrated in EN 15–16, the erosion progressed rapidly, expanding beyond the limits of the sports center and reaching side streets and avenues, leading to road closures. Large erosive processes in urban areas are historical in Umuarama, located in the Northwest Paraná region. Previous erosive processes were already stabilized in the watershed of the Pinhalzinho II stream in 2013, where the sports center is located. With the EN 15–16 event, the entire downstream fluvial system, which had vegetated and stable margins [32], returned to an expressive dynamic of marginal erosion and channel movement, due to the energy input (Figure 8).

Figure 8. Erosional feature (ravine) in a sport center located in the municipality of Umuarama (date of the photography: 10 December 2015). (**A**): Aerial images of the sports center area, from May 2013 and June 2016; the yellow circle represents the area of the photography above; (**B**) downstream area where the sediments were deposited; the red circle indicates sandy bars formed in the river channel. Source: Google Earth.

The works to contain erosive processes, drainage and recovery of the destroyed structures have had a major financial impact in the state and municipal budgets. Based on the occurrences observed in the field, in [28], and in media reports, a cartographic compilation of the effects that consecutive heavy rainfall has caused in the North of Paraná was developed (Figure 9). In this compilation, the processes were categorized as road interdiction, geomorphological processes, and interruption in the water supply. It can be observed that in the north-central region, there were many water shortage problems, especially in January 2016. It can also be noted that interdictions were numerous in the vicinity of Colorado, Paranavaí, and between Umuarama and Cianorte. Although interdictions also occurred in other areas, the role of the differences in soil characteristics between northwest and north-central Paraná is emphasized. Other areas of northern Paraná were also affected, especially by the rainfalls in early 2016, such as the region of Wenceslau Braz.

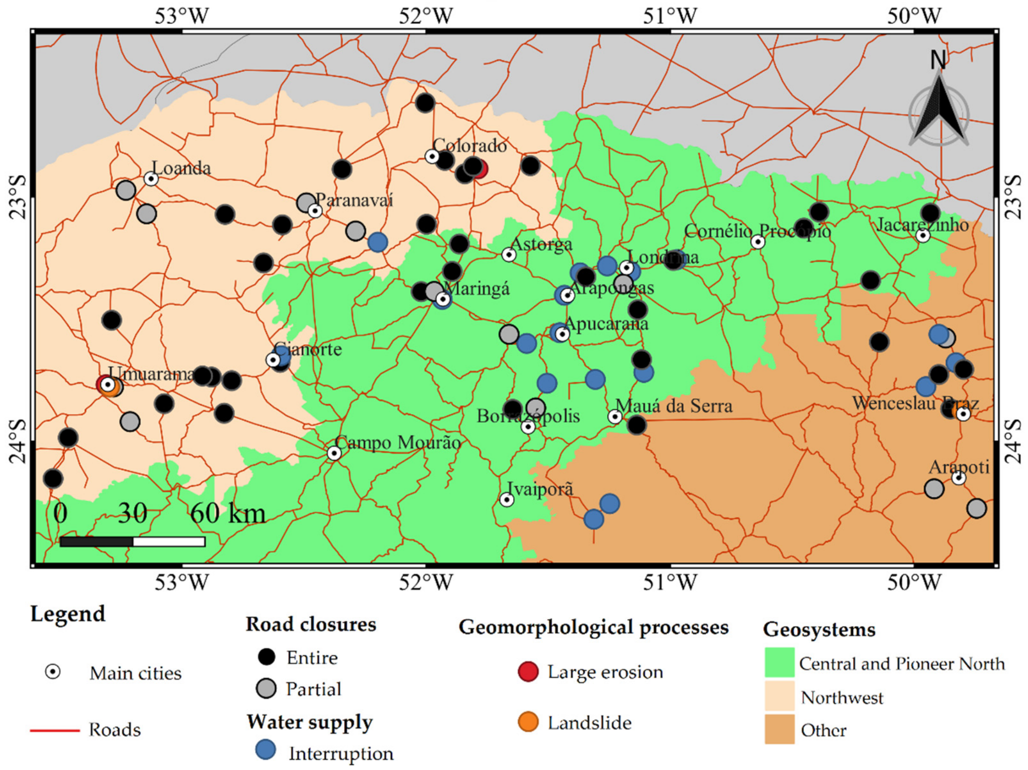

Figure 9. Compilation of processes resulting from the intense and continuous rainfall related with the EN 15–16 episode, in Northern Paraná, Brazil. Source: State limits and highways: IBGE.

Based on the observed and analyzed occurrences, a simplified conceptual scheme of the variables related to the effects of EN 15–16 in Northern Paraná is proposed (Figure 10). A spectral order is followed, in which the variables of the higher hierarchy are in warm colors (reddish) and those of the lower hierarchy are in cool colors (blue and violet). The various indices by which ENSO is evaluated [33] were considered, with emphasis on the variation in the distribution of the sea surface temperature (SST) in the Equatorial Pacific Ocean, representing the controlling variable of the highest order. Changes in atmospheric circulation, in turn, derive from changes in the pattern of the SST in the Pacific Ocean. One of the consequences of these changes is the increase in rainfall in the study area. From the yellow box (Figure 10), the variables and processes represented from the global scale (oceans and atmosphere) are interrelated to the regional scale (watershed).

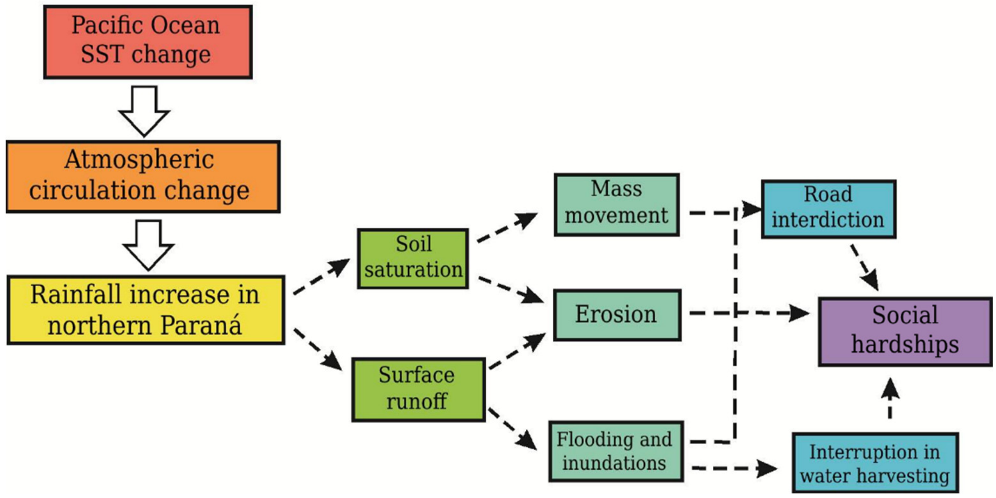

Figure 10. Conceptual flowchart of the hierarchy of variables related to geosystemic effects related with the EN 15–16 episode, in Northern Paraná, Brazil.

The rainfall increase triggers hydrological processes such as water saturation in the soil and decrease in infiltration. The first process contributes to the occurrence of landslides, while as a result of both, surface runoff is enhanced, which in turn leads to erosion and the river discharge increases. Regarding erosion first, this process has caused the interruption of traffic on several stretches of highway, the formation of gullies in urban areas, and soil erosion with the loss of nutrients and productivity in rural areas. The floods also caused road blockages, but the difference regarding the effects of erosion is that the flooding led to the interruption of the water collecting and supply. These processes caused social adversities, such as logistical problems and economic losses. Regional planning demands interdisciplinary analysis and public management [34,35] with risk mapping and technical communication interchange with civil engineers addressing infrastructure resilience.

4. Conclusions

The disturbances caused by rainfall with an expressive return period (>30 years, and >150 years in some locations) during EN 15–16 indicate the absence of resilience in landscape components in northwestern and northern Paraná. Based on the spatial distribution of these disturbances, the collapse of geosystem components was initially noted in the northwest (November/2015), while in the north-central and Pioneer North regions, it took the combination of a series of consecutive months with voluminous rainfall and a short period with extreme daily precipitation (early January/2016). We emphasize the role of the difference between lithologies and surface cover and even the characteristics of the existing local climates, which are associated with the regional climatic context that fostered the disturbances in the landscape. Studies in other regions of the world also highlight the role of ENSO in the climate variability that occurred in 2015–2016, with reduced rainfall and drought in some regions, and heavy rainfall and flooding in others, making it a complex phenomenon [36–38]. This disparity has also been reported in Brazil, where past El Niño events have accentuated periods of drought in northern states and of extreme precipitation and flooding in central and southern states. These ENSO-related extreme events have global socio-economic impacts, being amplified by underlying climate-change trends, as, for example, in the heightened risk of Amazon fires during the 2015–16 El Niño [39]. Lessons from landscape disturbances and a climate change scenario with extreme events reinforce the necessity of mapping and managing risk disasters with temporal and spatial scales of the rainfall return period.

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