INFLUENCE OF SEASONAL VEGETATION DYNAMICS ON HYDROLOGICAL CONNECTIVITY IN TROPICAL DRYLANDS

**ABSTRACT**

Seasonally dry forests in tropical regions show over 300% inter-annual biomass variability that directly affects the runoff and erosion dynamics. However, biomass fluctuation is mostly overlooked in hydrosedimentological analysis, including in connectivity analysis. The aim of this paper is to understand how the dryland vegetation seasonality in Brazilian drylands affects the potential runoff and sediment connectivity using the Index of Connectivity (stream and outlet targets). **Two main analytical steps were used to identify the influence of dry forest biomass fluctuation on connectivity: Creation of vegetation scenarios based on the relationship between rainfall patterns and NDVI fluctuations (Landsat images); Identification of the effect of the vegetation scenarios on Index of Connectivity. The method was applied to a 90km2 watershed, creating a daily vegetation classification using five Vegetation Scenarios related to rainfall parameters, with** average NDVI values from 0.18 during Very Dry Scenarios (<20mm of antecedent rainfall) to 0.62 in Very Wet Scenario (>500mm of antecedent rainfall). **The primary connectivity behaviour** is controlled by a continuous connectivity decrease, reaching 32%, related to increase of humidity and vegetation density. At the same time, due to rainfall irregularity, high magnitude rainfall events can occur even during Very Dry scenarios, when the watershed shows very high potential connectivity. It indicates that connectivity in runoff-dominated regions is temporally variable due to the highly seasonal vegetation and variable incidence of intense rainstorms.

**Keywords**: Potential flow connectivity; index of connectivity; tropical dryland; dry forest; biomass fluctuation; rainfall variability.

1. **INTRODUCTION**

Connectivity can be understood as the transmission capacity between landscape units and it can be used to understand the dynamics of hydrological fluxes of water, sediment and nutrients (Hooke, 2003; Wohl, 2017) . In some runoff-dominated areas, such as semiarid regions the functional connectivity is controlled by the rainfall-runoff-discharge relationship (Bracken & Croke, 2007; Figueiredo, Araújo, Medeiros, & Costa, 2016). Hydrological deficiency produces the predominance of Hortonian overland flow dynamics. This episodic hillslope dynamic is the primary controller of intermittent and ephemeral stream behaviours, creating a pulsed behaviour (Bracken & Croke, 2007; Hooke, 2016) that generate seasonal connectivity (intermittent) or short pulse connectivity (ephemeral). In tropical drylands such as found in NE Brazil, the seasonal dynamic of dryland vegetation, for example dry forest, is particularly strong  and is hypothesised to create a distinctive connectivity behaviour, based on rainfall-runoff-discharge pulses that are affected by the strong biomass seasonality. This has not been studied previously and is the topic of this research.

In drylands, the connectivity processes differ between hillslopes and in the fluvial domain. The Hortonian overland flow process on hillslopes is directly affected by the land cover and vegetation density and predominantly occurs where these are low. Only in some events does runoff reach the main channels; a runoff threshold between hillslope runoff and channel flow generation has been identified (Costa, Bronstert, & Araújo, 2012; Costa, Foerster, Araújo, & Medeiros, 2013) . The channel flow is affected by saturation levels of alluvial beds, common in drylands (Bull & Kirkby, 2002; Costa, et al., 2013; Figueiredo, Araújo, Medeiros, & Costa, 2016)**.**  Transmission losses in the sand and gravels of the channel mean that many runoff events during the dry season do not reach downstream areas, making discharge events and fluvial connectivity through the whole system highly episodic. These runoff events generate intra-basin sediment storage (López-Vicente & Navas, 2010), that can be reworked by the episodic discharge events.

Dryland areas in tropical regions differ from many of the semiarid regions in which connectivity has been studied in that they are characterised by higher temperature but also higher rainfall rates. For example, the Brazilian tropical semiarid zone has rainfall rates habitually between 500mm/year and 1000mm/year, whereas the Spanish semiarid zone has rainfall rates generally between 300 mm/year and 500mm/year. However, the net hydrological balance in the tropical zone is still one of deficit because of the high average potential evapotranspiration rates, which can reach annual values above 1600mm/year. The hydric deficiency in Brazilian drylands is determined by anticyclonic dynamics, as the primary control, creating a markedly dry season. Secondary regional controls, such as local topography or continentality effects, can decrease the rainfall rates and create conditions for the development of dry areas (Corrêa, Tavares, Lira, Mutzenberg, & Cavalcanti, 2019).

The higher rainfall rates generate a landscape arrangement in NE Brazil different from the other world drylands, especially producing a denser vegetation assembly. The contemporary literature classifies the Brazilian semiarid vegetation, locally called "*Caatinga*", as a neotropical dry forest. This classification is based on the evolution scenario and species assembly, density cover and phenology (Banda et al. 2016; Lima, Carvalho, Lima-Ribeiro, & Manfrin, 2018; Morrone, 2015). The most common trees/shrub in Caatinga are Spondias tuberosa, Caesalpinia pyramidalis, Ziziphus joazeiro, and Mimosa tenuiflora. Caatinga semi-deciduous/deciduous behaviour produces different biomass scenarios depending on the humidity available. The leaf recovery starts in the early rainy season and may last five months (Parente et al., 2012). The foliage fall begins after the wet season, with a peak in litter formation in the first two or three months of the dry season (Costa, Camacho, Macedo, & Silva, 2010; Lopes, Andrade, Lobato, Palácio, & Arraes, 2010; Parente et al., 2012) . The vegetation development, persistence and decline are affected by the amounts, length and timing of wet and dry periods. The density of vegetation influences the rate of biomass loss; dense vegetation helps to retain the soil moisture for more time. Rainfall also tends to be highly variable, both inter-annually and intra-annually. variability of tropical semiarid vegetation affects the runoff generation and the hillslope erosion.

Caatinga leaf area index (LAI) seasonality affects the structural connectivity, increasing hillslope connectivity when LAI is lower and decreasing the connectivity when LAI is higher. LAI drops markedly during the dry season until the early rainy season, reducing the vegetation cover, surface roughness and increasing raindrop impact, consequently raising the sediment yield (Andrade et al. 2018; Hoffman, Yizhaq, & Boeken 2013; Santos et al. 2017). In the following wet season the increase of vegetation density is reflected in the surface roughness increase, acting as a lateral buffer, especially to coarse sediment delivery (Borselli, Cassi, & Torri, 2008; Cislaghi & Bischetti, 2019; Poeppl, Keiler, Elverfeldt, Zweimueller, & Glade, 2012). Additionally, plant litter can reduce runoff and hydrological connectivity (Hoffman, Yizhaq, & Boeken, 2013). As a result, the first precipitation events of the rainy season, before the vegetation growth has fully responded, have the highest hillslope structural connectivity scenarios, resulting in higher sediment yield (Santos, Andrade, Medeiros, Guerreiro, & Palácio, 2017a), since LAI and litter are at their minimum.

The influence on connectivity in dryland Mediterranean and grassland woody vegetation of the characterise heterogeneous pattern of vegetation patches and bare areas, is well known (Bergkamp, 1998; Dickie & Parsons, 2012; Hoffman et al., 2013; Moreno-De-Las-Heras et al., 2020; Okin et al., 2015; Puigdefábregas, 2005; Puttock et al., 2013; Urgeghe & Bautista, 2015). In contrast, the role of tropical dryland forests, characterised by a continuous dense cover during the wet season and discontinuous sparse cover in the dry season (Lima et al., 2018), is little understood.

Although the importance of land cover to connectivity is well known, the analytical frameworks frequently neglect the vegetation influence on the surface dynamics (Graf et al., 2018; Lisenby & Fryirs, 2017; Messenzehl, Hoffmann, & Dikau, , 2014; Souza, Corrêa, & Brierley, 2016). One of the frameworks that allows analysis of the vegetation influence on connectivity is the Index of Connectivity – IC developed by Borselli, et al. (2008) specifically for this purpose. They proposed a method to calculate a continuous spatial analysis of potential connectivity between different parts of connectivity by a GIS model approach. Besides the topographical information, IC uses a weighting factor (W) to represent the surface runoff and sediment flux impedance elements, such as vegetation, land use management and soil characteristics (Borselli et al., 2008; Sougnez, van Wesemael, & Vanacker, 2011). The original IC (Borselli et al., 2008) used USLE/ RUSLE C-factor values as a W. It indicates the potential of the crop/management and vegetation cover for soil loss and its application enabled analysis of the land cover and vegetation influence on connectivity and how land cover changes impact connectivity dynamics (D’Haen et al., 2013; de Walque, Degré, Maugnard, & Bielders, 2017; Jamshidi, Dragovich, & Webb, 2014; Kumar et al., 2014; Lana-Renault et al., 2018; López-Vicente, Poesen, Navas, & Gaspar, 2013; López-Vicente & Álvarez, 2018), including dryland vegetation changes (Foerster et al., 2014; Lopes & Pinheiro, 2013).

The IC underwent a significant revision that modified, among other properties, the W from the C-factor to a Roughness Index – RI (Cavalli, Trevisani, Comiti, & Marchi, 2013). This RI assumes unvegetated areas and removes the vegetation cover influence as surface flux impedance, The modified IC-RI model became one of the most common connectivity analysis frameworks (Calsamiglia et al., 2018; Marchi, Comiti, Crema, & Cavalli, 2019; Messenzehl et al., 2014; Nicoll & Brierley, 2017; Schopper et al., 2019), mainly after the release of a free open-source tool – SedInConnect (Crema & Cavalli, 2018). Later, land cover information was re-introduced as a weighting factor, mainly using Manning's n roughness coefficient, to improve vegetated area analysis.

The most common technique used to analyse the relation between rainfall/moisture and the vegetation stage is one of the remote sensing vegetation indices, like NDVI (Schulz, Koch, Cierjacks, & Kleinschmit, 2017). The relationship between rainfall and NDVI in drylands could be understood as linear or exponential, depending on the data and vegetation type (Almeida-Filho & Carvalho, 2010; Brinkmann, Dickhoefer, Schlecht, & Buerkert, 2011). Also, each dryland vegetation type will respond to rainfall events at different velocities and rates (Omuto, Vargas, Alim, & Paron, 2010). Because of this complex behaviour, it is necessary to analyse the rainfall-NDVI relation of each type of dryland vegetation. As an example of Caatinga biomass variability, the same vegetation arrangement can display, depending on the antecedent rainfall, NDVI values around 0.2, savanna-like, to values around 0.6, rainforest-like, reaching in some places values over 0.8 (Souza, 2019). NDVI analysis indicates the actual biomass density (Cabrera-Bosquet et al., 2011) and can be related to soil protection and surface roughness transmission impediment. Consequently, it can define the IC weighting factor ( Ortíz-Rodríguez, Muñoz-Robles, & Borselli, 2019; Singh & Sinha, 2019).

This research aims to investigate how the seasonal fluctuation in the dry forest biomass density, characteristic of tropical drylands and exemplified by the Brazilian semiarid region, affects the runoff and sediment connectivity over time. The vegetation density fluctuation is controlled by the rainfall seasonality/irregularity and affects hydrological and sedimentological surface dynamics and this relationship is quantified and applied to create vegetation scenarios. The Index of Connectivity is used to analyse and to spatialise the influence and patterns of potential water and sediment connectivity changes under the different vegetation scenarios related to the hydrological variations.

1. **STUDY AREA**

The Brazilian drylands, located in NE Brazil between latitudes 2.7º S and 18º S (Fig. 1), cover an area of 974,752 km², typically with average annual rainfall under 800mm, aridity index up to 0.5 and drought risk higher than 60%. The landscape is characterised by lowlands in crystalline and metasedimentary rocks, and residual landforms structured on raised sedimentary basins, high-grade metamorphic bands, or more resistant plutonic intrusions (Corrêa et al., 2019).

The Intertropical Convergence Zone (ITCZ) controls the hydrology of the semiarid areas, with the rainy season between three to six months (generally between November-June depending on the region), and average annual rainfall between 400-800mm. The rainfall is directly affected by the oceanic-atmospheric climatic conditions, mainly the El Niño/Southern Oscillation and Pacific Decadal Oscillation, producing strong rainfall fluctuation between different years (Barbosa, Huete, & Baethgen, 2006; Barbosa & Kumar, 2016; Barbosa et al., 2019). At the same time, the potential evapotranspiration can reach annual values around 2000mm (Costa, Becker, & Brito, 2013). Furthermore, high areas, above 700 meters, show an increase in the humidity due to orographic effect, especially above 900 meters, creating 'sub-humid islands' (Souza, Almeida, & Corrêa, 2015; Souza et al., 2016).

The water scarcity, including low groundwater availability led to widespread construction of surface water reservoirs during the last century (Costa et al., 2013; Peter et al., 2014). The water available for agricultural purposes is mainly supplied by small rural reservoirs and shallow wells in alluvium areas. The domestic supply to the major villages and towns is provided by medium and large reservoirs, as well as, in some places, by deep groundwater (Costa et al., 2013; Araújo et al., 2004; Peter, Araújo, Araújo, & Herrmann, 2014). There is no mechanism of water release in the small and medium reservoirs; only some of the large reservoirs have this type of structure. Thus, the reservoirs act as a significant impediment to sediment connectivity. There is a partial connection scenario between upstream and downstream only when the reservoirs are full, and overflow occurs (Peter et al., 2014; Souza et al., 2016).

**The Jeremias Dam Watershed has a catchment area of 92 km2 and shows representative social-environmental characteristics of the crystalline (igneous and metamorphic rocks) areas of the Brazilian Drylands. It is** situated in the Borborema Highlands (Fig 1) between the summit surfaces (granitoids) and the intermontane depressions (meta-sedimentary and meta-volcanic rocks) (Corrêa et al., 2019). **This region has 740mm/year average rainfall, with** rainfall fluctuation from 203mm/year to 1224mm/year,  **and shows mainly natural vegetation (Chaves,** Francisco, Lima, & Chaves**, 2015), with crops, predominantly beans and maize, covering around 8% of the basin.**

1. **METHODOLOGY**

Two main analytical steps were taken to identify the influence of dry forest biomass fluctuation on connectivity (Fig. 2): (1) Create vegetation scenarios based on the relationship between rainfall patterns and natural biomass variability; (2) Identify the effect of vegetation scenarios on connectivity in rainfall events.

The first step of the research was to understand how the biomass density changes over time and seasonally and what is the relationship between these changes and the rainfall characteristics. Based on this relationship, it was possible to create five different vegetation scenarios each associated with a rainfall/humidity scenario. The second step was to calculate the potential Index of Connectivity for each one of these scenarios, to be able to understand how the natural vegetation dynamics can influence the runoff and sediment connectivity. These results were then used to analyse the sediment connectivity routes and the relation to vegetation changes and fragmentation, analysing hillslope profiles and channel profiles, for each vegetation scenario and set of rainfall events.

* 1. **Vegetation scenarios and rainfall relationships**

Landsat-5/TM image scenes were acquired between September 1999, the beginning of the hydrologic year, and August 2010, with less than 5% of cloud cover being selected and 30m of spatial resolution, totalling 39 images. This period, 1999 to 2010, shows an excellent annual rainfall variability, and is representative of the Brazilian tropical semiarid zone (Costa et al., 2013). There were no significant land cover changes between 1998 and 2010, with the watershed population density oscillating between 22 pop/km² in 2000 to 24 pop/km² in 2010.

NDVI was calculated for the watershed area, following Jensen (2014), to identify the vegetation dynamics of all the images with <5% of cloud cover inside the watershed area. NDVI shows satisfactory results to determine the seasonality of dryland vegetation, including the primary production of the herbaceous stratum ( Barbosa et al., 2006; Brinkmann et al., 2011; Chen & Gillieson, 2009). It is essential to emphasise the importance of the herbaceous stratum in increasing surface roughness and consequently decreasing the sediment connectivity.

The vegetation density is affected not only by the last rainfall events but also by the rainfall amount of at least two years before (Barbosa et al., 2019; Souza, 2019). Because of that, daily rainfall data were collected between 01/09/1997 and 30/08/2010 from a rain gauge located at the Jeremias Dam. The average NDVI of each image was used to analyse the relationship between the NDVI and rainfall characteristics. Two main rainfall characteristics, with variations, were examined for each satellite image NDVI scene; 1. Dry days since last rainfall event of 0.1mm, 10mm and 25mm (Aviad, Kutiel, & Lavee, 2009); 2. Antecedent Cumulated Rainfall (ACR) for 5, 10, 20, 30, 60, 120, 180, 365 days before. As secondary data, water volume data of Jeremias Dam, in the outlet of the basin, were used to identify the discharge volumes, as there is no flow gauge in the channels.

The NDVI image results were grouped by their average NDVI values in five vegetation scenario groups: Very Low Density (<0.19), Low Density (0.19-0.26), Average Density (0.26-0.35), High Density (0.35-0.6), and Very High Density (>0.6). These threshold values were defined based on standard vegetation classifications (Ballén, Souza, & Lima, 2016; Brinkmann et al., 2011; Lucena, Pires, & Filgueira, 2018; Nascimento, Lima, & Lima, 2014; Quevedo & Francés, 2008): bare land and sparse vegetation (0.19), savanna (0.26), shrubland (0.35), dry forest (0.6), and rain forest (>0.6). For each group, a mean NDVI image was calculated using map algebra, creating one representative Vegetation Scenario Image for each one of the density groups and named according to the vegetation classes. These classes/ranges match well known NDVI vegetation responses and biomass density. The vegetation classes can also be applied to spatial patterns of density within original individual images. The dams show irregular water body extensions (0.7% to 0.07% of the basin area), related to the previous discharge amount but some scenes show them as dried out, with bare ground or sparse vegetation. Therefore, all the water areas are classified as "bare land and sparse vegetation”. Using this method all areas are classified according to their density typical of a vegetation type. An area can vary in its classification over time, allowing a clear representation of biomass seasonality between the Vegetation (Density) Scenarios. It is not a classification of the vegetation.

The connectivity is directly affected by the vegetation density at each rainfall event. Due to the *Caatinga* biomass density fluctuation, it is necessary to identify the actual density at each rainfall event. The main problem is the small collection of cloud free satellite images, so there are large periods with no NDVI values. Therefore the rainfall/NDVI relations were used to define the Vegetation Scenario seasonality over time based on rainfall parameter limits. The 120 days ACR was found to provide the best correlation between rainfall parameters (r²= 0.834, see results) and Vegetation Scenario seasonality. Using this relation it was possible to determine the probable vegetation density for all the rainfall events and apply this to connectivity analysis.

**3.2 Potential connectivity and Index of Connectivity**

The Index of Connectivity – IC (Borselli, et al., 2008) calculates the potential connectivity, which uses topographical and land use characteristics to understand the potential connectivity from the erosion process in hillslopes to the sediment transport through hillslopes and stream channels.



The index uses the potential hydrology topographical factors as the main controller elements to connectivity, namely, slope gradient (S), length of the downstream path (d), upslope contributing area (A), and a weight factor (W). The SRTM (Shuttle Radar Topography Mission, available on: https://earthexplorer.usgs.gov/) with 30m resolution was used as topographic information. Cavalli et al. (2013) presented several modifications to the initial index,; two of them were the use of DInfinity algorithm and the index calculation to different targets (streams and outlet). They changed the D8 algorithm to D-infinity to calculate flow direction that allows the identification of flow direction in areas with dispersive flow; this change is widely used as a better algorithm (Lana-Renault et al., 2018; López-Vicente & Álvarez, 2018; Messenzehl et al., 2014; Nicoll & Brierley, 2017; Ortíz-Rodríguez et al., 2017; Persichillo et al., 2018; Schopper et al., 2019). Calculation of the index for different targets (streams and outlet) allows separate identification of the potential for transmission all the way between any catchment point/cell to the watershed outlet (outlet IC), or between a catchment/hillslope point/cell to the closest selected stream (stream IC) (Calsamiglia et al., 2018; D’Haen et al., 2013; Schopper et al., 2019; Tiranti, Crema, Cavalli, & Deangeli, 2018). The outlet IC shows a lower index in the headwaters (points far from the outlet) and higher index next to the watershed outlet. The present research used the Dinfinity algorithm, calculated to the two different target sinks, outlet\_IC and stream\_IC. To identify the stream for stream-IC a catchment area threshold of 0,243km² for stream initiation was used, following the standard regional behaviour (Souza & Almeida, 2014).

The calculations used the USLE/RUSLE C-factor as W factor. C-factor can be related to each dryland vegetation density/stage, (Foerster et al., 2014) based on research on runoff, infiltration, erosion, sediment transport, models and experimental plots effects of different vegetation, including *Caatinga* areas and similar vegetation stages/densities and rainfall seasons (Figueiredo et al., 2016; Santos, et al., 2017a; Santos, et al, 2017b; Santos, 2017c; Xavier et al., 2016). The use of different C-factors for each density class in each rainfall/vegetation scenario makes it possible to understand how the natural *Caatinga* dynamic affects the potential connectivity. In this way, the C-factor was defined, based on the literature (Anache et al., 2017; Andrade et al., 2017; C. A. Lima et al., 2013; Palácio et al., 2016) for the different densities: bare land and sparse vegetation (0.5), savanna (0.11), shrubland (0.04), dry forest (0.0167), and rain forest (0.0004). To understand the vegetation seasonality impact on the connectivity the IC models were run for each Vegetation Scenario, allowing creation of five Connectivity Scenarios.

The last stage was to analyse the vegetation/connectivity scenario fluctuations over time based on rainfall-vegetation relation. In addition, the distribution of extreme rainfall events over the different connectivity scenarios was identified to understand their occurrence over the range of vegetation scenarios and therefore their potential impact.

1. **RESULTS**

**4.1 Vegetation scenarios and rainfall relationships**

There are 176 Landsat 5 images between September 1999 and August 2010, but only 39 were used to calculate the NDVI index (covering all the months), due to the cloud cover. Initially, all the NDVI images were organised by their average NDVI value; the lowest values were found on the image of 29/11/2003 and the highest on 19/06/2008, showing an average NDVI of 0.179 and 0.655 respectively, and a maximum of 0.609 and 0.811.

Analysis of the relationship between the average NDVI value and various rainfall characteristics showed the highest correlations to be to the Antecedent Cumulated Rainfall (ACR) for 90, 120 and 180 days (Table 1), (r²= 0.724, 0.834 and 0.790, respectively), so these were used to identify the vegetation density stage. The number of dry days since last rain had a low coefficient of determination (r² = 0.319 with 25mm rainfall), so is not as satisfactory to identify vegetation density stage.

Average NDVI separates the images into five groups that tend to be strongly associated with ACR parameters (Table 2), as shown by the correlations above. These are termed: Very Low Density (<0.19), Low Density (0.19-0.26), Average Density (0.26-0.35), High Density (0.35-0.6), and Very High Density (>0.6). Table 1 indicates that actual rainfall values of the best ACR parameters vary in each group. Furthermore, analysis reveals that 365 days ACR can affect the NDVI (Souza, 2019). This can be observed in the responses to the 24/01/2007 image when even with 0mm for 120 days ACR, it does not show one of the lowest average NDVI values, probably because of the influence of high rainfall volume in the year before these dates (above 800mm/year). In the opposite behaviour, the 25/08/2003 image had a higher ACR of 116.7mm and 252.9mm, respectively for 120 days and 180 days, but a low average NDVI value, 0.228, which can be explained by the effect of a very dry year before this date (391.6mm/year).

A second step was to use the 120 days ACR parameter to create a continuous classification of vegetation seasonality. Four 120 days ACR limits based on the rainfall characteristics in each Landsat image date (Table 1) – 20mm, 60mm, 250mm and 500mm – were used to produce groups of hydrological scenarios (Very Dry Scenario <20mm; Dry Scenario 20-60mm; Average Scenario 60-250mm; Wet Scenario 250- 500mm; and Very Wet Scenario >500mm). The daily Vegetation Scenarios, from 01/09/1997 to 30/08/2010, were then classified according to these ACR limits An average NDVI scene, as land cover and vegetation maps, was calculated for each ACR scenario class (Fig. 3), based on the NDVI values of all images of each group. Table 2 indicates the average composition of each vegetation density type for each scenario. After this classification it was possible to apply the ACR120 to identify the daily Vegetation Scenario of the whole period analysed (September 1999 to August 2010), enabling understanding of the vegetation density seasonality over time (Table 2).

The Very Dry and the Dry scenarios display a concentration of area classified as bare land and sparse vegetation, and savannah densities. Nevertheless, even in dry moments, some areas can reach values of Dry forest density, normally riparian vegetation, as the map distribution shows (Fig. 3-A-B). At the same time, some areas classified as bare land, sparse vegetation and savannah densities, do not respond to the rainfall. These areas can be associated with degraded areas, rocky outcrops and lake areas (dry during most of the time). The NDVI value distribution shows two main "limits", a low one around 0.15/0.18 and a high one around 0.7. The low one shows a peak in the Very Dry scenario that represents the lowest natural level of vegetation density reduction of the *Caatinga* vegetation and a second one is close to the maximum natural level of *Caatinga* density expansion.

The analysed period showed a dispersion between scenarios, with the Average Scenario representing 33.5% of the time, with average 120 days ACR of 148.3mm. The Very Wet scenario is restricted to 13,8% of the time and showing an average of 709.4mm for 120 days ACR. At the same time, NDVI scenario images show average and maximum values between 0.182 and 0.522 (Very dry Scenario) to 0.626 and 0.773 (Very Wet scenario). The maximum values are lower than the values from the individual images because when the average values are calculated, these peaks are smoothed. Vegetation density class distributions show a high variability of response in the different vegetation scenarios. One of the highlights is the high biomass density during the Very Wet scenarios, when 71.8% of the area shows NDVI similar to a rainforest, with a high surface coverage preventing rain splash effect and runoff and increasing the surface roughness and infiltration. The vegetation maps show clearly an extensive natural and dominant variability of vegetation density over time, where 45.8% and 24.8% of areas change from a level of biomass density similar to sparse vegetation and savannah respectively, during the driest moments, to a stage with a biomass density similar to rainforests, during the wettest moments (Fig. 4).

**4.2 Connectivity responses**

The IC results (Table 3) show the variability in the potential Index of Connectivity for the analysed area. Two main behaviours are explicit; the connectivity decreases with the increase of humidity and vegetation density and the range scale differs between IC\_Outlet and IC\_Stream. As a result, the Index of Connectivity decreases from the Very Dry scenario to the Very Wet scenario; for example, the average IC\_outlet decreases 46.2% between the Very Dry and Very Wet scenarios.

The range scale variation is controlled, basically, by the decrease of the downstream distance component, with the IC\_Outlet being much longer than IC Stream (confined to hillslopes) The IC\_Outlet values produced are between 41% and 24% lower than the IC\_Stream, in Very Dry scenarios and Very Wet scenarios, respectively. The decrease of the index values from driest to most humid scenarios is related to sensitivity to the index of the ratio between the topographic and vegetation elements. When there is a low vegetation density scenario, the topographical features, as downstream distance, are highlighted, increasing the difference between IC\_Outlet and IC\_Stream. During the high vegetation density scenarios, the vegetation processes minimise the topographic controls and consequently decrease the difference between the indexes. Understanding these differences, it is clear the impossibility to directly compare the two indexes. In this way, the IC\_Stream shows the potential connectivity between slope-stream, and the IC\_Oulet shows the possibility of a particle moving from one point through the hillslope and streams to the outlet.

Five potential connectivity categories (Very Low, Low, Average, High and Very High) were created to spatialise the Index of Connectivity. Jenks natural breaks were used to define the category limits (Persichillo et al., 2018; Tiranti et al., 2018) in the data of all five vegetation scenarios for each index (IC\_Outlet and IC\_Stream) (Fig. 5 and 6). Jenks natural breaks is a data clustering method that minimises average deviance from each class mean, being the pattern of choropleth mapping (Chen et al., 2013). Due to the scale difference between the indexes, this process was executed separately, so the limits are different for the two indexes.

The indexes are a result of the interaction of stable topographical parameters (mainly slope angle, catchment area and downstream distance to the sink) and dynamic vegetation characteristics, based on the C-factor values. As the particle goes downstream, it gets closer to the sink, also increasing the potential connectivity to the sink area (streams or outlet). These behaviours generate a constant rise in the potential connectivity downstream, insofar as the catchment area increase gives a higher possibility of a more significant flow and transport possibilities. This continuity is affected by changes in the slope angle and the land cover, with these elements acting as boosts or barriers/buffers to the connectivity. The IC\_Outlet maps (Fig. 5) show clearly the connectivity increasing in the direction of the outlet, though, in general, the vegetation acts to decrease the connectivity while its density increases. The IC\_Stream maps (Fig. 6) show more balanced results focused on the hillslopes, due to the decrease of the influence of downstream distance and catchment area parameters. It is affected by topography but the central control to this index is the vegetation density, repeating a similar behaviour to the relationship between vegetation and connectivity of the IC\_Outlet model. These differences between the indexes emerge again when comparing the areas by the potential connectivity classes in each vegetation scenario (Table 4). The main difference is the higher percentages in the very high connectivity class of the IC\_Stream model compared with the IC\_Outlet; as an example, in the Very Dry Scenario the percentage increases from 16,8% to 35,8%, between IC\_outlet and IC\_Stream respectively. This difference implies that there is a higher possibility of transport of material between the hillslope to the channels than transport of material through the watershed to the outlet.

**4.3 Rainfall events and vegetation/connectivity relationship**

Comprehension of the magnitude, frequency, and temporal/spatial distribution of the rainfall events is crucial to understand the functional connectivity because it is in these events that flow of water and sediment can take place. As shown, the natural vegetation dynamics play a major role in the connectivity likely to occur. Consequently, a high magnitude event could trigger a different connectivity dynamic depending on the vegetation scenario. It makes it necessary to analyse the rainfall patterns in relation to the classified vegetation scenarios.

The monthly rainfall behaviour can be easily observed by the detailed analysis of the rainfall events between September 1997 and August 2010 (Fig. 7). The low concentration of rainfall events between August and November, mostly events under 25 mm is evident. This period is directly correlated with the decrease of biomass density, controlled by the retraction of herbaceous stratum and leaf fall of caducifolious/semi-caducifolious species. The second point is the irregular fluctuation of the Antecedent Cumulated Rainfall, with occurrence of hydrological years that did not show the Very Wet scenario (1997/1998, 1998/1999, 2000/2001, 2002/2003, 2004/2005). In specific years, due to a broader temporal rainfall distribution, the vegetation density can be maintained at Average Scenario, for example, from January 2000 to September 2001.

Moreover, it is crucial to understand that the monthly fluctuation (Table 5) between these vegetation scenarios can happen at different times during the hydrological year, or even not occur in specific years, mainly in the extreme scenarios. Nevertheless, there is one wet period between April and June, and one well-marked dry period, October to December. Between April and June, there is a probability of over 70% of days in Wet and Very Wet scenarios and no likelihood of Dry scenarios. In contrast, between October and December, there is no possibility of Wet scenarios, with over 70% chance of Dry and Very Dry scenarios. Otherwise, there are some transitional months, like August, January and February, that show the occurrence of all the different scenarios. Concomitantly, the rainfall events occur in all the months, and the high magnitude events, above 50mm, can occur before, during or after the rainy months (January to April). One of the highlights is the high magnitude rainfalls (above 25mm) in December, with a 0.57 event/year recurrence time, that impact a scenario mostly with no dense vegetation cover (84.2% probability of Very Dry or Dry scenario). Additionally, due to the scenario fluctuation, different vegetation scenarios can occur in all the months, highlighting January and February when such days happened in all five vegetation scenarios, during the time analysed (01/09/1997 and 30/08/2010).

A detailed analysis of the rainfall events (Table 6) shows a distribution of varying magnitude rain events during all scenarios, but concentrated in the Average (31%), Wet (29.9%) and Very Wet (29%) vegetation scenarios. Concentration to these periods is higher for lower magnitude events, when 91.5% and 91.4% of the events under 10mm and between 10 to 25mm respectively occur, whereas for high magnitude events, concentration drops to 82% of rainfall events over 50mm in the wetter scenarios. These high magnitude events have a higher probability of generating runoff, discharge, erosion and sediment transport, which is enhanced if they occur when there is low vegetation density. At the same time, these rainfall events, above 50mm, represent 7.1% of total rainfall events but 26.9% of total rainfall volume, which emphasises the importance of these events.  The analysis reveals that these high magnitude events can occur during all the vegetation stages, including the Very Dry and Dry scenarios, when around 80% and 60% of the watershed shows very high and high potential connectivity to IC\_Stream model.

In the study period of 13 years, 32 high magnitude rainfall events (over 50mm) were identified, with a frequency of 2.43/year, of which the heaviest events were around 140mm/day (Table 7). The possibility of high magnitude events in different vegetation scenarios highlights the impact of these events over a range of different potential connectivity conditions. It can be observed by the events of 02/01/2010 (140.3mm in a Dry scenario) and of 20/03/2009 (144.3mm in a Wet scenario). The high-intensity event of 02/01/2010 affects a scenario with 61% of high and very high connectivity, on the IC\_stream model, generating runoff, erosion and sediment transport between the hillslopes and the channels. In contrast, the 20/03/2009 event falls on a scenario with 57% of low and very low connectivity.

1. **DISCUSSION**

The relationship between ACR and NDVI showed similar responses to field monitoring experiments that included soil moisture measurements. Leaf growth lasts two to five months after the rainy season begins, and leaf fall and litter production peaks in the first two and three months after the rainy season ends, depending on the species and water availability (Costa et al., 2010; Lopes et al., 2010; Parente et al., 2012). The litter cover after the first months after the rainy season acts to decrease the connectivity but, as it is not green matter, it is not detected by NDVI. Nevertheless, the use of ACR 120 days could cover the growth phases, as well as indirectly the litter presence. At the same time, discrepancies between ACR 120 and NDVI values correlating with preceding extreme climate years (very dry or very wet years), reflect the field behaviour. In these cases, for example, after an extremely rainy year, the vegetation reaches a very high expansion stage, and the biomass density helps to retain the soil moisture and biomass density (Cunha et al., 2014). That exposes how sensitive Caatinga is to climate fluctuation, and, consequently, climate change ( Araújo et al., 2004; Souza & Oyama, 2011). For example, during the 2012-2017 drought period, there was an extreme decrease of biomass in this region (Ferreira da Silva et al., 2020), when the low rainfall rates of one year affected the next year. As a secondary point, the divergences could be related to small convective rain cells, the predominant rainfall mechanism in the area (Souza et al., 2015). These cells can generate localised rainfall not recorded by the rain gauge network, affecting the correlation results of ACR and NDVI.

It is essential to observe that all the NDVI images showed maximum values above 0.6, similar to tropical rainforest density (Mallmann et al., 2015), even during the driest stage. It is important to underline that Caatinga vegetation (dry forest) has a direct evolutionary link with Brazilian rainforests (Santos et al., 2007). These high NDVI values during dry scenarios could be related to areas where there are wetter surface and subsurface hydrological conditions, such as in riparian areas (Albano et al., 2020). These areas display water concentration mechanisms and can maintain native perennial riparian species and exotic perennial invasive species, such as the regionally common *Prosopis Juliflora* (Nascimento et al., 2014; Trovão et al., 2010). As a complementary pattern, areas next to the channels are also the concentrated agricultural areas, due to the better water availability and increase in soil depth and fertility (Almeida-Filho & Carvalho, 2010).

In general, the response of NDVI values to climate pattern revealed a sequential fluctuation related to the rainfall patterns that allowed us to define vegetation scenarios based on defined ranges of ACR120 days. This method avoids uncertainties in Caatinga classification NDVI threshold (C. Nascimento et al., 2013; S. Nascimento et al., 2014), helping to understand the dryland vegetation fluctuation patterns, including as a reflex to soil moisture (Román-Cascón et al., 2020).

The vegetation density fluctuation directly affects the Index of Connectivity values, decreasing 46.2% and 60.2% from the Very Dry to Very Wet Scenario, in IC\_Outlet and IC\_Stream, respectively. This result shows a cyclic pattern where the same area could be disconnected at one time, and connect in a different time (Lopes & Pinheiro, 2013). These differences show the importance of land cover to the model, decreasing the effect of the topographical parameters. Vegetation seasonality effect on connectivity is poorly understood, with some efforts to analyse the effects of seasonal crops (Singh & Sinha, 2019), vegetation density changes by wild fires (Ortíz-Rodríguez et al., 2019), or vegetation types classified by seasonality (Foerster et al., 2014).

Besides the land cover parameter, the pattern of high connectivity values next to the outlet is enhanced by the coupled response to downstream distance and cell catchment area parameters. This effect is even higher for elongated-shape watersheds (D’Haen et al., 2013; Messenzehl et al., 2014). Only very steep or flat slopes overshadow this arrangement. Simultaneously, in Brazilian drylands, these very steep slopes usually represent the most preserved vegetation areas (Bispo et al., 2010), as these areas were not suitable for agriculture.

The IC\_Outlet model analyses the whole watershed connectivity, encompassing the hillslopes and channels connectivity process. There is no parameter in the indexes that allows to understand the transmission loss in hyporheic zones (Costa et al., 2012; Costa et al., 2013). On alluvial bed channels, predominantly sand bed, the saturation of the sediment layer is the primary condition for discharge generation, being directly related by the antecedent runoff/precipitation events (Costa et al., 2013). During the dry scenarios/moments, most of the runoff flow infiltrates the alluvial beds, generating none or very low discharge events, as can be identified by the low recharge on the Jeremias Dam by the 02/01/2010 event of 140,3 mm, that increased the storage from 75.3% to 80.9% (increase of 142,988 m3). Alternatively, after the 20/03/2009 event of 144,3.mm, the reservoir level increased from 34.2% to 84.4% (increase of 1,882,176 m3), representing a 12 times higher discharge level. Therefore, probably, the high magnitude event in the dry period had a low water and sediment connectivity in the streams, whereas the same event in the wet scenario had high connectivity.

Otherwise, on hillslopes, the occurrence of high magnitude events during scenarios with higher potential connectivity (three over Very Dry and three over Dry vegetation density scenario in the analysed period) can generate high rates of water and sediment transmission, runoff and hillslope erosion. The individual high-intensity rains are even more critical to a runoff-dominated geomorphological system, such as that analysed here, than in a saturated-runoff system (Bracken & Croke, 2007; Figueiredo et al., 2016). In contrast, high magnitude events which occurred over Very Wet (six events), and Wet (ten events) vegetation density scenarios had the hillslope connectivity processes buffered (dos Santos et al., 2017). This behaviour represents the typical hillslope dryland processes where pre-rainy season rains generate a small portion of the total annual runoff, but are responsible for substantial erosion volume due to the significant exposure of the soils (Lima et al., 2013; Palácio et al., 2016; Santos, et al.,2017). Simultaneously, it is important to emphasise the highly variable monthly rainfall behaviour, indicating that the vegetation fluctuation analysis should be done by the precipitation behaviour not by fixed seasons or months. Another key parameter to understand the runoff and sedimentological responses is the rainfall intensity, but it depends on sub-daily rain data, which is not common in poorly monitored dryland areas.

 As a result, runoff events in the drier scenarios generate high connectivity on the hillslopes and low connectivity in the channels. The material transported during these events can at first create alluvial fans on the floodplains or alluvial beds, due to the connectivity loss. Alternatively, the runoff events during the wetter scenarios generate, on the hillslopes, high hydrological connectivity, due to soil saturation, and low sediment connectivity, due to the vegetation protection. The Index of Connectivity results were adequate to model hillslope connectivity processes but not the alluvial channel behaviour.

It is important to highlight this connectivity behaviour should be similar to other seasonal dry biomes areas, constituting half of tropical areas (Pennington et al., 2018). These seasonal dry biomes include zones such as dry forests in Central and South America (Banda et al., 2016; Lima et al., 2018; Gerard et al., 2020), dry forests in Horn of Africa region (Van Passel et al., 2020), and sub-Saharan tree savannas (Räsänen et al., 2020). These biomes exhibit continuous ground cover, mainly during wet season, contrasting with subtropical/Mediterranean drylands, with interchanges between vegetation patches and bare areas (Bergkamp, 1998; Dickie & Parsons, 2012; Hoffman et al., 2013; Moreno-De-Las-Heras et al., 2020; Okin et al., 2015; Puigdefábregas, 2005; Puttock et al., 2013; Urgeghe & Bautista, 2015).

1. **CONCLUSIONS**

The Caatinga vegetation, typical of this dryland region of NE Brazil, exhibited an average NDVI fluctuation between 0.18 and 0.62, equivalent to a range from bare land/ Sparse vegetation to rainforest, with the vegetation density having a very strong seasonal and interannual variation. The vegetation density has a high correlation to the 120days Antecedent Cumulative Rainfall, but is also affected by the average rainfall amount of the last years. The strong relationship established between rainfall and NDVI values makes it possible to identify the vegetation dynamics and create five different vegetation density scenarios, typical of each rainfall pattern represented by ACR 120 days parameter.

The vegetation density seasonality affects the connectivity, increasing from 0,5% to 68.2% Very Low Connectivity areas from Very Wet to Very Dry Scenarios, in IC\_Stream models. The higher difference found in IC\_stream than IC\_Outlet results shows the increase of the importance of the land cover to the model, and replicates the behaviour found by field monitoring data.

The connectivity processes are related to the temporal distribution of the rainfall/runoff/discharge over the different vegetation density scenarios. It is necessary to analyse the structural connectivity, represented by vegetation cover, and its temporality to understand the functional connectivity in runoff-dominated regions with highly seasonable biomass density behaviour. The data show that the vegetation fluctuation analysis should be done by continuous parameters, such as Antecedent Cumulated Rainfall, not by fixed seasons or months. Using the scenarios created, the impact of individual rainfall events of various magnitude can be assessed and the conditions for maximum connectivity of runoff and of erosion and sediment flux in such an environment of high vegetation seasonality can be identified.

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**TABLES**

Table 1: Average NDVI values for each satellite image and Antecedent Cumulated Rainfall (ACR) value. The images are separated by average NDVI into five groups – Very Low Density (under 0.19); Low Density (from 0.19 to 0.26); Average Density (from 0.26 to 0.35); High Density (from 0.35 to 0.6); and Very High Density (over 0.6).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **ACR (mm) - 90 days** | **ACR (mm) - 120 days** | **ACR (mm) - 180 days** | **NDVI –** **maximum** | **NDVI –** **average** |
| 29/11/2003 | 15.9 | 15.9 | 57.8 | 0.609 | 0.179 |
| 12/07/2006 | 0.0 | 0.0 | 28.5 | 0.669 | 0.185 |
| 13/11/2003 | 15.9 | 15.9 | 67.8 | 0.652 | 0.190 |
| 17/10/1999 | 0.0 | 26.9 | 177.8 | 0.674 | 0.193 |
| 10/12/2003 | 5.8 | 37.5 | 138.3 | 0.745 | 0.195 |
| 18/11/2005 | 0.0 | 0.0 | 73.3 | 0.685 | 0.200 |
| 11/02/2005 | 0.0 | 0.0 | 83.3 | 0.669 | 0.206 |
| 09/10/2003 | 37.5 | 57.7 | 238.7 | 0.683 | 0.212 |
| 22/10/2001 | 0.0 | 55.0 | 126.6 | 0.610 | 0.215 |
| 15/09/1999 | 26.9 | 69.7 | 177.8 | 0.712 | 0.216 |
| 11/10/2008 | 14.0 | 41.0 | 55.1 | 0.658 | 0.225 |
| 13/01/2009 | 0.0 | 0.0 | 41.0 | 0.696 | 0.226 |
| 11/04/2000 | 71.3 | 91.7 | 124.5 | 0.611 | 0.227 |
| 10/01/2005 | 0.0 | 58.0 | 222.1 | 0.680 | 0.228 |
| 28/12/2008 | 0.0 | 4.0 | 41.0 | 0.691 | 0.228 |
| 24/01/2007 | 0.0 | 0.0 | 0.0 | 0.693 | 0.231 |
| 25/08/2003 | 51.9 | 116.7 | 252.9 | 0.679 | 0.243 |
| 09/12/2004 | 38.9 | 71.3 | 80.9 | 0.709 | 0.256 |
| 10/04/2006 | 0.0 | 57.7 | 283.7 | 0.706 | 0.260 |
| 28/08/2010 | 83.6 | 103.0 | 337.4 | 0.703 | 0.262 |
| 13/11/2009 | 22.4 | 68.9 | 238.3 | 0.724 | 0.268 |
| 15/12/2009 | 0.0 | 22.4 | 90.1 | 0.705 | 0.274 |
| 23/09/2008 | 41.0 | 55.1 | 378.4 | 0.738 | 0.294 |
| 09/02/2006 | 57.7 | 120.4 | 560.2 | 0.726 | 0.319 |
| 10/03/2000 | 91.7 | 116.2 | 270.7 | 0.725 | 0.352 |
| 31/05/2001 | 227.2 | 262.4 | 351.7 | 0.740 | 0.358 |
| 06/09/2010 | 257.8 | 328.5 | 583.0 | 0.756 | 0.374 |
| 24/05/2010 | 278.2 | 334.7 | 579.0 | 0.762 | 0.428 |
| 15/05/2001 | 227.2 | 262.4 | 351.7 | 0.753 | 0.492 |
| 07/10/2004 | 59.9 | 59.9 | 832.0 | 0.776 | 0.518 |
| 04/05/2004 | 811.3 | 811.3 | 821.4 | 0.772 | 0.555 |
| 08/09/2009 | 243.3 | 717.4 | 1085.7 | 0.761 | 0.568 |
| 07/05/2008 | 239.1 | 748.5 | 893.8 | 0.797 | 0.603 |
| 14/06/2006 | 538.5 | 782.4 | 784.2 | 0.800 | 0.604 |
| 13/04/2001 | 257.9 | 347.2 | 349.7 | 0.809 | 0.611 |
| 19/04/2009 | 627.5 | 627.5 | 627.5 | 0.805 | 0.616 |
| 07/08/2009 | 523.9 | 825.1 | 1151.4 | 0.800 | 0.646 |
| 05/02/2008 | 754.6 | 776.6 | 797.6 | 0.808 | 0.646 |
| 19/06/2008 | 461.8 | 789.9 | 893.8 | 0.811 | 0.655 |

Table 2: NDVI and vegetation density class for each Vegetation Scenario: Very Dry scenario with ACR 120days under 20mm; Dry scenario with ACR 120days between 20mm and 60mm; Average scenario with ACR 120days between 60mm and 250mm; Wet scenario with ACR 120days between 250mm and 500mm; Very Wet scenario with ACR 120days over 500mm.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Very dry scenario** | **Dry scenario** | **Average scenario** | **Wet scenario** | **Very Wet scenario** |
| **GENERAL CHARACTERISTICS** |
| **Average ACR (mm) - 120 days** | 6.8 | 38.7 | 148.3 | 340.9 | 709.4 |
| **Standard deviation ACR (mm) - 120 days** | 7.1 | 13.2 | 52.6 | 65.4 | 137.6 |
| **Scenario days (%)** | 18.1% | 14.1% | 33.5% | 20.5% | 13.8% |
| **NDVI CHARACTERISTICS** |
| **Average NDVI** | 0.1821 | 0.2182 | 0.2794 | 0.4555 | 0.6259 |
| **Maximum NDVI** | 0.522 | 0.586 | 0.639 | 0.676 | 0.773 |
| **Standard deviation NDVI** | 0.036 | 0.048 | 0.068 | 0.089 | 0.105 |
| **VEGETATION DENSITY CLASSES AREA (%)- 09/1999 to 08/2010** |
| **Bare land and sparse vegetation density** | 66.8% | 22.5% | 3.1% | 2.3% | 1.3% |
| **Savannah density** | 29.8% | 64.8% | 32.5% | 0.8% | 1.3% |
| **Shrubland density** | 3.2% | 10.9% | 54.0% | 8.1% | 0.7% |
| **Dry forest density** | 0.3% | 1.8% | 10.3% | 86.9% | 24.8% |
| **Rain forest density** | 0.0% | 0.0% | 0.0% | 1.9% | 71.8% |

Table 3: Potential Index of Connectivity values – IC\_Outlet and IC\_Stream – for the five vegetation scenarios

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Potential Index of Connectivity scenarios** | **Minimum** | **Maximum** | **Mean** | **Standard Deviation** |
| **Very Dry Scenario – IC\_Outlet** | -8.271 | 0.343 | -5.146 | 0.660 |
| **Dry Scenario – IC\_Outlet** | -8.271 | 0.052 | -5.483 | 0.687 |
| **Average Scenario– IC\_Outlet** | -9.449 | -0.349 | -5.885 | 0.663 |
| **Wet Scenario – IC\_Outlet** | -9.885 | -0.817 | -6.402 | 0.648 |
| **Very Wet Scenario – IC\_Outlet** | -10.301 | -1.145 | -7.523 | 0.983 |
| **Very Dry Scenario – IC\_Stream** | -7.060 | 0.223 | -3.646 | 0.716 |
| **Dry Scenario – IC\_Stream** | -7.060 | -0.183 | -3.988 | 0.719 |
| **Average Scenario– IC\_Stream** | -8.024 | -0.832 | -4.395 | 0.709 |
| **Wet Scenario – IC\_Stream** | -10.301 | -1.017 | -4.914 | 0.709 |
| **Very Wet Scenario – IC\_Stream** | -10.301 | -0.941 | -6.050 | 1.044 |

Table 4: Potential Index of Connectivity classes for each vegetation scenario in IC\_Outlet and IC\_Stream models

|  |
| --- |
| **POTENTIAL CONNECTIVY INDEX (OUTLET – IC\_Outlet)** |
|  | **VERY LOW CONNECTIVITY** | **LOW CONNECTIVITY** | **AVERAGE CONNECTIVITY** | **HIGH CONNECTIVITY** | **VERY HIGH CONNECTIVITY** |
| **VERY DRY SCENARIO** | 0.6% | 4.9% | 18.8% | 58.9% | 16.8% |
| **DRY SCENARIO** | 1.7% | 11.3% | 35.7% | 42.1% | 9.2% |
| **AVERAGE SCENARIO** | 4.9% | 28.1% | 41.4% | 21.8% | 3.8% |
| **WET SCENARIO** | 19.9% | 50.0% | 22.5% | 5.9% | 1.7% |
| **VERY WET SCENARIO** | 73.3% | 17.9% | 5.6% | 2.2% | 1.0% |
| **POTENTIAL CONNECTIVY INDEX (STREAM – IC\_Stream)** |
| **VERY DRY SCENARIO** | 0.5% | 3.8% | 15.3% | 44.6% | 35.8% |
| **DRY SCENARIO** | 1.4% | 8.8% | 28.3% | 41.2% | 20.2% |
| **AVERAGE SCENARIO** | 4.1% | 21.8% | 37.1% | 28.0% | 9.0% |
| **WET SCENARIO** | 15.9% | 41.1% | 28.4% | 11.9% | 2.7% |
| **VERY WET SCENARIO** | 68.2% | 18.4% | 8.7% | 3.6% | 1.1% |

Table 5: Rainfall pattern of the period between 01/09/1997 and 30/08/2010 separeted by ACR 120 days limits. Very Dry scenario with ACR 120days under 20mm; Dry scenario with ACR 120days between 20mm and 60m; Average scenario with ACR 120days between 60mm and 250mm; Wet scenario with ACR 120days between 250mm and 500mm; Very Wet scenario with ACR 120days over 500mm.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Very Dry scenario** | **Dry scenario** | **Average scenario** | **Wet scenario** | **Very Wet scenario** |
| **RAINFALL FREQUENCY AND MAGNITUDE EVENTS (%)** |
| **Rainy days > 0.1mm (34.7 events/year)** | 4.7% | 5.3% | 31.0% | 29.9% | 29.0% |
| **Total rainfall volume (683.8mm/year)** | 6.2% | 6.9% | 29.7% | 32.0% | 25.1% |
| **Rainy days – 0.1-10mm (12.5 events/year – 35.9%)** | 3.7% | 4.9% | 32.1% | 29.0.% | 30.2% |
| **Rainfall volume – 1-10mm (61.3mm/year – 9.0%)** | 4.3% | 5.7% | 35.0% | 26.7% | 28.2% |
| **Rainy days – 10-24.9mm (11.7 events/year – 33.7%)** | 4.6% | 3.9% | 31.6% | 30.3% | 29.6% |
| **Rainfall volume – 10-24.9mm (167.5mm/year – 24.5%)** | 5.1% | 3.9% | 31.7% | 29.8% | 29.5% |
| **Rainy days – 25-49.9mm (8.1 events/year – 23.3%)** | 5.8% | 7.3% | 29.2% | 30.7% | 27.0% |
| **Rainfall volume – 25-49.9mm (271.3mm/year – 39.7%)** | 6.9% | 8.2% | 28.3% | 33.5% | 23.1% |
| **Rainy days > 50mm (2.5 events/year – 7.1%)** | 9.4% | 9.4% | 31.3% | 31.3% | 18.8% |
| **Rainfall volume > 50mm (183.7mm/year – 26.9%)** | 8.7% | 11.2% | 27.2% | 36.5% | 16.3% |
| **POTENTIAL CONNECTIVY INDEX (STREAM – IC\_Stream)** |
| **VERY LOW CONNECTIVITY** | 0.50% | 1.40% | 4.10% | 15.90% | 68.20% |
| **LOW CONNECTIVITY** | 3.80% | 8.80% | 21.80% | 41.10% | 18.40% |
| **AVERAGE CONNECTIVITY** | 15.30% | 28.30% | 37.10% | 28.40% | 8.70% |
| **HIGH CONNECTIVITY** | 44.60% | 41.20% | 28.00% | 11.90% | 3.60% |
| **VERY HIGH CONNECTIVITY** | 35.80% | 20.20% | 9.00% | 2.70% | 1.10% |

Table 6: Monthly behaviour between 01/09/1997 and 30/08/2010: magnitude and frequency of rainfall events and vegetation scenarios.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| - | **SEP** | **OCT** | **NOV** | **DEC** | **JAN** | **FEB** | **MAR** | **APR** | **MAY** | **JUN** | **JUL** | **AUG** |
|  | **NUMBER OF RAINFALL EVENTS** |
| **Rainy days – 0.1-10mm** | 5 | 1 | 2 | 6 | 17 | 14 | 29 | 30 | 23 | 20 | 9 | 6 |
| **Rainy days – 10-24.9mm** | 1 | 1 | 1 | 3 | 20 | 28 | 26 | 24 | 22 | 13 | 8 | 5 |
| **Rainy days – 25-49.9mm** | 1 | 0 | 0 | 4 | 13 | 17 | 27 | 23 | 10 | 9 | 1 | 0 |
| **Rainy days – >50mm** | 0 | 0 | 0 | 3 | 7 | 3 | 10 | 5 | 4 | 0 | 0 | 0 |
|  | **PERCENTAGE OF DAYS IN EACH SCENARIO** |
| **Very Dry scenario** | 7.7% | 41.7% | 72.6% | 66.3% | 19.9% | 3.8% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 4.0% |
| **Dry scenario** | 33.1% | 37.7% | 14.6% | 17.9% | 35.2% | 15.5% | 6.0% | 0.0% | 0.0% | 0.0% | 4.5% | 5.0% |
| **Average scenario** | 56.4% | 20.6% | 12.8% | 15.9% | 38.0% | 53.7% | 34.5% | 21.0% | 11.9% | 25.6% | 41.9% | 71.0% |
| **Wet scenario** | 2.8% | 0.0% | 0.0% | 0.0% | 6.0% | 19.1% | 48.6% | 39.0% | 43.4% | 39.0% | 33.3% | 14.9% |
| **Very Wet scenario** | 0.0% | 0.0% | 0.0% | 0.0% | 1.0% | 7.9% | 10.9% | 40.0% | 44.7% | 35.4% | 20.3% | 5.2% |

Table 7: High magnitude rainfall events, over 50mm, vegetation scenario and 120days Antecedent Cumulated Rainfall

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Date** | **Rainfall volume (24h)** | **Vegetation scenario (cumulative rainfall 120 days)** | **Date** | **Rainfall volume (24h)** | **Vegetation scenario (cumulative rainfall 120 days)** |
| **20/03/2008** | 144.3 | Wet Scenario (308.7mm) | 10/03/2001 | 60.5 | Average Scenario (152.2mm) |
| **14/04/2009** | 143.9 | Wet Scenario (473.3mm) | 29/04/2002 | 59.7 | Very Wet Scenario (601.3mm) |
| **02/01/2010** | 140.3 | Dry Scenario (52.4mm) | 06/12/2005 | 58.2 | Very Dry Scenario (5mm) |
| **27/01/2004** | 112.0 | WScenario (412.7mm) | 05/04/2002 | 56.3 | Wet Scenario (490.6mm) |
| **25/05/2002** | 105.5 | Very Wet Scenario (562.2mm) | 01/03/2007 | 56.3 | Average Scenario (185.3mm) |
| **23/12/1999** | 97.0 | Very Dry Scenario (7.5mm) | 01/03/2000 | 56.0 | Wet Scenario (372.6mm) |
| **06/03/2002** | 95.0 | Wet Scenario (287.6mm) | 28/02/2004 | 55.5 | Very Wet Scenario (746.7mm) |
| **15/05/1999** | 91.2 | Average Scenario (174.2mm) | 12/02/2008 | 54.4 | Dry Scenario (43mm) |
| **02/03/2006** | 89.0 | Wet Scenario (277.7mm) | 17/04/2000 | 54.0 | Very Wet Scenario (502.6mm) |
| **15/01/2004** | 86.7 | Average Scenario (102.4mm) | 11/01/1999 | 52.3 | Very Dry Scenario (0mm) |
| **22/01/2004** | 76.0 | Average Scenario (235.1mm) | 21/03/2010 | 52.2 | Wet Scenario (330.5mm) |
| **07/04/2009** | 73.4 | Wet Scenario (382.7mm) | 07/05/2002 | 51.4 | Very Wet Scenario (514mm) |
| **24/03/1998** | 73.0 | Dry Scenario (54.3mm) | 23/02/2006 | 51.0 | Average Scenario (146.3mm) |
| **01/03/2006** | 65.2 | Average Scenario (212.5mm) | 14/03/2008 | 50.8 | Average Scenario (209.9mm) |
| **10/05/2008** | 64.4 | Very Wet Scenario (794.9mm) | 08/12/2005 | 50.2 | Average Scenario (74.2mm) |
| **05/01/2002** | 63.0 | Average Scenario (74.3mm) | 25/01/2004 | 50.0 | Wet Scenario (331.8mm) |

**FIGURE LEGENDS**

Figure 1: Top – Landscape Units of the Brazilian Dryland and the Jeremias Dam Watershed. Bottom – Jeremias Dam watershed topography; left – a Digital Elevation Model; right – Slope angles.

Figure 2: Methodological flowchart

Figure 3 Average land cover and vegetation map:. A – Very Dry scenario with ACR 120days under 20mm. B – Dry scenario with ACR 120days between 20mm and 60mm. C – Average scenario with ACR 120days between 60mm and 250mm. D – Wet scenario with ACR 120days between 250mm and 500mm. E – Very Wet scenario with ACR 120days over 500mm.

Figure 4: Natural vegetation dynamics. Top row: 1 – Very Dry Scenario with 10mm (ACR 120days) at 30/10/2016. 2 – Average Scenario with 103mm (ACR 120days) at 29/09/2010. 3 – Wet Scenario with 260mm (ACR 120days) at 20/11/2010. Bottom row: A – Very Dry scenario. C – Average scenario. D – Wet scenario.

Figure 5: Potential Index of Connectivity of Outlet target – IC\_Outlet to different vegetation scenarios A – Very Dry scenario. B – Dry. C – Average scenario. D – Wet scenario. E – Very Wet scenario.

Figure 6: Potential Index of Connectivity of stream target – IC\_Stream to different vegetation scenarios A – Very Dry scenario. B – Dry. C – Average scenario. D – Wet scenario. E – Very Wet scenario.

Figure 7: Rainfall events (mm) and 120days Antecedent Cumulated Rainfall (mm) between 01/09/1997 and 30/08/2010.